D. DETERMINATION OF EFFECT

Having discussed measurement of ambient levels and exposure, the independent variables of damage functions, we are now ready to tackle the dependent variable, i.e., the associated effect. Subsequent sections will address establishment of functional relationships and presentation of results. The presentation here comprises an introduction, followed by an examination of the effects of air pollution on health, vegetation, and materials.

1. Definitions

Precise definition of the effect under study is perhaps the most important requirement in the successful development of a damage function. Such a definition revolves around the following attributes:

- Type of effect
- Duration
- Reversibility
- Sensitivity
- Specificity
- Threshold and saturation
- Measures.

These are now discussed in turn.

Terms commonly used to denote effect include response, injury, and damage. The first of these implies a change in the activity of the subject and is thus not applicable to the numerous situations where the subject is inanimate. Injury is a more general and applicable term for observable effect. Finally, damage is injury of such type and magnitude that it affects the normal function of the subject. The definition of damage also includes functional aggravation of a preexisting injury and predispostion to future damages.

For example, initial injury to the surface of a leaf or the paint coat of a steel girder is generally not regarded as a damage, unless and until it threatens the strength of the latter and the metabolic function of the former. However, the same injury would be considered damaging, if the paint served an additional aesthetic function and the leaf were used as cigar wrapper stock.

Duration of damages provides for their classification as chronic or acute. The former typically result from long-term exposure to low concentrations of pollutants, are characterized by extended duration of development, delayed detection, and long prevalence, and may be illustrated by most forms of cancer. Because of these characteristics, development of damage functions involving chronic effects is very difficult. Acute effects, usually associated with short-term exposure to high pollutant levels, are characterized by very rapid development and detection and rather brief and dramatic effects, such as the "excess" deaths registered during a severe air pollution "episode". It should be noted, however, that long-term, low-level exposure is also likely to provide a predisposition to acute effects, and conversely, one or more short-term high-level exposures could eventually produce chronic effects.

A related aspect of biological damages is reversibility, i.e., the ability of the subject to repair the damage and restore the function, upon cessation of exposure. A good example of reversible damage is low-level intoxication with carbon monoxide. On the other hand, exposure to even low levels of certain heavy metals leads to their accumulation in the body organs, and eventually, irreversible damage.

The type and severity of effects resulting from a given exposure to a specific pollutant are governed in large measure by the sensitivity and susceptibility of individual members or classes of the population. The distinction drawn here between susceptibility and sensitivity is somewhat arbitrary, but useful. Members of a given species, such as Homo sapiens, tend to have a similar sensitivity to the effects of air pollution, in the sense that their tissues are likely to experience a similar effect, upon a given exposure to a specific pollutant. However, the very young, the very old, and people afflicted with other disorders are more susceptible to observable damage, such as illness or death. Various plant species, on the other hand, differ in sensitivity to air pollutants and may be bred with this trait in mind. In such a case, the cost of breeding the resistant variety and any associated loss in productivity must be included in the calculation of total economic damage.

In assessing specific effects of a given level of exposure, it is very important to isolate the influence of any cofactors and mimics. The former are factors that act simultaneously, synergistically, or antagonistically with the pollutants. This may be illustrated by the dramatic influence of moisture in the corrosive effects of sulfur dioxide on metals. On the other hand, photochemical oxidants appear to act antagonistically toward sulfur dioxide, perhaps by forming a protective metal oxide film. Mimics are factors that simulate the effect of certain pollutants. A classic example is that presented by ozone and nuclear radiation, both of which cause disruption of chromosomes. Because of their large variety and importance, cofactors and mimics will be taken up in greater detail under the individual target areas below.

The concept of exposure threshold has been the subject of considerable and heated debate in connection with establishment of air quality standards. This concept holds that, for every specific combination of pollutant, cofactors, effect, and population at risk, there exists an initial level of exposure up to the threshold value, which is not associated with significant, or at least, observed damage. Conversely, one can also postulate a saturation level of exposure, resulting in extreme effects (e.g., destruction of the target population), such that additional exposure does not result in additional observed damage.

The common practice of setting air quality standards at, or just below the corresponding threshold levels has engendered considerable controversy, which revolves around the various possible interpretations of the threshold concept. Since threshold levels are largely contingent on the ability to observe and measure small degrees of damage in large populations, they become continually eroded with improving state of the art in damage assessment. Moreover, it is known that low levels of certain pollutants which are incapable of producing measurable damages, nevertheless generate a predisposition to subsequent damage. Thus, the proponents of reduced standards advocate that these be set at 1-3 orders of magnitude below threshold levels, depending on the gravity of the corresponding damage, to ensure public safety. Opponents argue that the economic costs and other deprivations associated with controls required to achieve such low standards cannot be justified by these benefits.

The final and most consequential attribute of effect is its measurement. Inasmuch as this study is concerned with physical, rather than economic damage functions, all damages are expressed in physical or biological, rather than monetary terms. Typical general measures of damage are the severity of effect summed over the population at risk, or the number or fraction of individual members affected. Specific measures vary widely from one target area to another and are thus best tackled under the several target areas below.

2. <u>Health Effects</u>

The target category of health effects refers primarily to the effects of air pollutants on human health, since most animals are not permitted to live long enough to suffer appreciable damages from prevailing pollutant concentrations. The major considerations here are the types of effects experienced, the effects of specific pollutants and cofactors, and the specific measures of damage.

The types of effects of air pollutants on human health, in order of increasing severity, are:

- Body burden
- Uncertain physiological changes
- Adverse physiological changes
- Morbidity
- Mortality.

At any given level of exposure, the fraction of the population affected decreases with increasing severity of effect, but damages in all of these categories must be included in the total figure.

Body burden, i.e., the accumulation of air pollutants (e.g., heavy metals), or their products (e.g., carboxyhemoglobin) in body organs and tissues, is the earliest indication of potential effect. This type of effect can be measured most reliably. Uncertain physiologic changes may involve decreased tolerance for exercise and changes in heart beat and blood pressure. Examples of adverse physiologic changes are eye irritation, coughing, and increase in electrocardiographic abnormalities.

Morbidity and mortality are by far the most common types of health effects investigated in the pursuit of damage functions. Large amounts of historical data are available from the National Center for Health Statistics, the National Heart and Lung Institute, the National Cancer Institute, and state departments of health. In most cases, the data are broken down by specific disorder, and sometimes, by demographic and/or socio-economic characteristics of the population at risk.

Measures of morbidity include incidence (number of new cases per unit time) and prevalence (number of continuing cases per unit time) of disease, hospital admissions and occupancy, medical visits, absenteeism from school and work, and personal record of discomfort. Some of these can be measured with greater reliability than others but most rely on weak reporting procedures. Mortality data suffer from occasional errors in diagnosing the cause of death, especially in the absence of an autopsy. Thus, specific heart ailments may be improperly identified and metastasized cancers mistaken for primary ones. Most importantly, there is no attempt to recognize combined effects, such as aggravation of the cause of death by another pollution-induced disorder.

The specific health effects of major air pollutants are listed in Table 20. It will be noted that aggravation of respiratory and cardiovascular diseases are the most common effects.

Table 20. Health Effects of Major Air Pollutants

Effect	Pollutants			
	SO_x/ Particulates	NO_x	Oxidants	CO
Aggravation of respiratory disease	X	X	X	
Aggravation of cardiovascular disease	X	X	X	X
Suspected contribution to respiratory neoplasms	X	X	X	
Suspected contribution to gastrointestinal neoplasms	X			
Reduced lung function	X		X	
Eye irritation	X		X	
Chronic nephritis		X		
Impaired exercise tolerance and mental activity				X

The principal cofactors of air pollutants in human health effects are the meteorological conditions of temperature and humidity. Factors affecting susceptibility of the population at risk, such as smoking habits, occupational exposure, and general health, are accounted for in characterizing the population at risk.

3. Vegetation Effects

Effects of air pollutants on vegetation are manifested through physiological changes, various types of injury to leaves and other parts of the plant, reduced yield, reduced plant growth, and, of course, death. The relative consequences of the various types of effect depend on the plant species and use. Thus, leaf appearance is of paramount importance in the case of cigar tobacco, lettuce, and ornamentals, fruit yield is important in the case of fruit trees, whereas plant growth is a principal consideration in raising livestock fodder.

The most remarkable feature of past measurements of air pollutant effects on vegetation is their wide diversity. This frustrates any attempts at verifying, comparing, or aggregating the results of different studies. The problem is illustrated in Table 21 which shows the effect, the measurement technique, and the plant investigated.

Table 21. Measurement of Vegetation Effects

Effect	Measurement Index	Plant
Physiologic Change	Evapotranspiration	Tobacco, soybean
	Absorption of CO_2	Pine
	Chlorophyll content	Tomato, pinto bean
Injury	Portion of leaf area affected	Nearly all plants studied
	Time to appearance	Elm, maple, ginko
	Leaf drop	Orange, lemon, pine
Growth Reduction	Weight	Ryegrass, soybean, birch
	Height	Cotton, poinsettia
	Diameter	Poinsettia, pine, poplar
	Number of leaves	Ryegrass
Yield	Number of flowers	Cotton
	Number of fruits	Cotton, orange, lemon, tomato
	Fruit drop	Orange
	Weight	Soybeans, corn, potato, tomato, spinach, radish, lettuce, alfalfa, orange, lemon
	Time to appearance	Corn, carnation, geranium, poinsettia, orange
Death		Mosses, lichens

Leaf injury may take the form of chlorosis - loss of chlorophyll manifested by appearance of light-colored areas, senescence - aging of tissues with concomitant changes in pigmentation, and necrosis - death of tissues evidenced by appearance of brown or black spots. Severity of injury is expressed as the percentage of leaf area affected or the time to appearance of the injury. Extent of leaf injury has been used with some success to predict yield loss from sulfur dioxide and fluorides, but not from ozone. This may be associated with the fact that the former pollutants accumulate in the plant tissues to produce leaf injury, whereas ozone affects permeability of the cell membrane and interferes with normal function of the chlorophyll.

Major cofactors in effects of air pollutants on vegetation are meteorological conditions, such as humidity, precipitation, insolation, temperature, and air turbulence, as well as soil moisture and nutrient content. Mixtures of sulfur dioxide and nitrogen dioxide may produce synergistic effects. However, sulfur dioxide and ozone may produce effects that are synergistic, antagonistic, or merely additive, depending on concentration ratio and plant species. Insects, diseases, drought and inadequate nutrition can produce effects that mimic those of air pollutants.

4. Material Effects

Effects of air pollutants on materials are rather well defined in comparison with health or vegetation effects. This is due to the higher uniformity of samples, simpler damage mechanisms, and consequently, greater reproducibility of results. The principal effects may be classified as soiling, fading, coating, corrosion, and degradation.

Soiling of building and other exposed surfaces occurs through deposition of particulate matter. The resultant damage is measured in terms of change in surface reflectance, or more subjectively, in terms of the frequency and effort of cleaning. Fading of textile dyes and paints, attributed primarily to nitrogen oxides and oxidants, may be assessed by subjective inspection or optical measurements. Changes in the tensile strength of textiles, rubber, and leather products provide a measure of the degradation of these materials by sulfur dioxide and/or oxidants.

Corrosion and degradation of metal and masonry surfaces can take place through disruption of a protective coating (e.g., the oxide coating on aluminum), formation of an undesirable coating (e..g., the sulfide coating on copper or silver), and formation of a soluble compound or powder that is washed or blown away (e.g., zinc or calcium sulfate). Corrosion and degradation mar the appearance and reduce the strength of the materials which then require periodic surface refinishing or replacement. These effects can be measured in terms of changes in weight, thickness, or electric resistance of a metal contact.

The more important factors affecting the attack rate of materials by damaging pollutants include humidity, temperature, sunlight, and air turbulence. Humidity is particularly effective in the corrosion of metals and the critical value which produces a sharp rise in corrosion rate varies between 60-90 percent, depending on the specific pollutant and target metal. Wind speed is significant in enhancing the contact of pollutants, including abrasive particles, with the material surface. Elevated temperature generally increases the rate of chemical attack. Sunlight contributes to the formation of photochemical oxidants, but also mimics the rubber cracking and dye fading effects of ozone.

Presence of particulates appears to increase the corrosion rate of metals by sulfur dioxide. However, photochemical oxidants tend to reduce this rate, perhaps by forming a protective metal oxide coating.

E. ESTIMATION OF FUNCTIONAL RELATIONSHIP

Once the exposure and effects data have been collected through one of the types of studies discussed in the preceding section, it becomes necessary to apply various statistical methods to estimate the corresponding dose-effect relationships. These techniques, the inherent assumptions and errors, and the types of ensuing relationships are taken up here.

1. Statistical Methods

In classical hypothesis testing, it is usually assumed that the functional specification of the relationship being examined is given and that the relevant variables are known. Procedures can then be adopted from statistical theory to test competing hypotheses. In examining air pollution dose-effect associations, however, the functional form of the relation is seldom known, and there are only conjectures as to all the relevant factors. Nevertheless, it is often necessary for investigators to assume a functional form of a dose-effect relation and test it to see how well the data fit the assumption or whether modifications must be made, or alternative methods used.

The more common statistical methods for defining the quantitative relationship between exposure and effect are:

- Cross tabulations or simple correlations
- Multivariate regression analysis
- Distribution-free analysis.

The first method has been used in the health effects area to correlate the prevalence of a disese in specified population groups with an index of air pollution. The difficulty in using the results of such a study is that a host of other factors are allowed to vary across populations and it is usually impossible to identify the pure pollution effect.

Recognizing the need to control for confounding factors affecting dose-effect relationships, some investigations cross-tabulate along several dimensions. For example, a statistical analysis of pollution effects on house paint might collect data for different areas of the country on the frequency of repainting, the levels of air pollution, and several meteorological variables. One could then compile either cross-tabulations based on the different variables or partial correlations. However, even this method will not produce reliable estimates of the dose-effect relation if the areas being compared are not well matched with respect to other important factors (e.g., types of buildings, or painting techniques).

A classic statistical method in epidemiological studies involves "purification" of the data by holding constant a number of factors. To this end, investigations of health effects have focused on persons of the same occupation and living in the same community, on the assumption that uncontrolled factors would be constant or vary randomly. However, a number of such studies suffer from large sampling variations induced by small sample sizes.

2. Multivariate Regression Analysis

Multivariate regression analysis of large populations has been used effectively to define the dose-effect relationship in health effects studies through statistical control of the interfering factors. The two basic types of multivariate analyses in this application use cross-sectional and time-series data, respectively. The first of these investigates a measured effect (e.g., mortality rates) across regions with different air pollution levels, while controlling for other regional differences, such as socioeconomic characteristics (Lave and Seskin, 1973). The second type of investigation examines changes in a measured effect within a single location as a function of changing air quality over a period of time (Glasser and Greenburg, 1971).

The major advantages of the time-series approach are that many of the covariates that could distort the results remain relatively constant within a region and that it permits assessment of lag effects. On the other hand, time-series analysis correlates current effects with current or lagged measures of exposure, even though these effects reflect preponderantly prior exposure, probably at lower concentration levels. Thus, this approach is better suited to investigation of acute than of chronic effects. Moreover, this approach is subject to difficulties introduced. by the assumption of serial independence of successive deviations between estimated and observed values.

The operation of multivariate regression analysis can be best illustrated by a simple two-variable case. The standard procedure for analyzing the relationship between the two variables is to fit a line through the observations using an ordinary "least squares technique", which minimizes the sum of squared vertical distances between the actual observations and the fitted line. The output consists of the best, linear, unbiased estimates of the slope and intercept. In the case of several independent variables, the results include coefficients which indicate the correlation between each independent variable and the dependent variable.

If the relationship is not approximated well by a linear equation, several other approaches can be used. A common procedure is to perform piecewise linear regressions by approximating several segments of the curve by linear functions. Another is to employ the cumbersome polynomial multivariate regression analysis. A third method is probit analysis, which usually involves representation of the independent variable on a logarithmic scale and expression of the dependent variable in terms of the probability unit (Finney, 1971).

Multivariate regression analysis has a number of important advantages:

- It provides a rapid estimate of the degree of association between a number of independent variables and the dependent variable
- If the independent variables are standardized, the individual regression coefficients can reveal the contribution of both "strength" and "sense" of each independent variable to the dependent variable
- It accounts for "unexplained" variations in the independent variable
- The required computer programs and know-how are widely available.

The limitations of this method are substantial, but can be mitigated somewhat by adroit statistical techniques.

- It requires a priori specification of an approximating relationship between each independent variable and the dependent variable
- Users frequently assume a linear relationship, and hence, the additive character of contributions of the independent variables
- Users frequently employ incorrectly an unweighted version that requires independent and randomly distributed errors in the dependent variable, with negligible randomness in the independent variables
- Regression coefficients are very sensitive to outlying data points.
- Regression coefficients are quite imprecise if the independent variables are closely correlated.

3. Distribution-Free Analysis

If the assumptions about distribution and relationships of the variables cannot be justified, the analyst has recourse to what is referred to as a distribution-free or non-parametric method of analysis. This method places little emphasis on population parameters, because the objective is to avoid a particular form for a population distribution. The hypotheses to be tested usually relate to the nature of the distribution as a whole, rather than to the values assumed by some of its parameters. This method of analysis can be implemented by comparing medians, means, ranges, ranks, or other classifications of data.

A distribution-free analysis based on medians was used to good advantage in investigating the health effects of sulfur oxides and nitrogen dioxide (Sprey and Takacs, 1973). The procedure may be outlined as follows:

- The range of each of the n independent variables is divided into classes (or levels)

- For each n-way classification of the data, the medians (or specified percentile) of the dependent and independent variables are computed

- The median of the first independent variable is plotted against the median of the dependent variable by classes of the first independent variable at various levels of the successive independent variables.

The set of medians are then estimates of the response of the dependent variable to all combinations of levels of the independent variables. Individual pairs of medians can be tested for statistically significant differences using standard median tests.

Another illustration, based on comparison of ranks, may involve the comparison of some measure of an air pollutant between Regions A and B, where n randomly selected samples of the air pollutant measured are available from each region. One can rank these 2n samples on the basis of their numerical values. The sum of the n ranks for Region A is then a measure of its overall pollution level. The minimum value that this sum can take occurs when each of the n values in Region A is smaller than the smallest value measured for Region B. Conversely, the maximum value that this sum can take, occurs when each of the n values in Region A is larger than the largest value measured for Region B. If Regions A and B have the same overall pollution levels, we would expect this sum to lie approximately half-way between its minimum and maximum values. The distribution of this sum is readily calculable without any assumptions regarding the actual distribution of the pollutant levels within either of the regions, thus providing a distribution-free method for comparing the pollutant levels of the two regions.

The principal advantages of the distribution-free method of analysis are:

- Freedom from assumptions about distribution and relative dimension of errors

- Freedom from assumptions about *a priori* knowledge and/or linearity of the relationships between independent variables and the dependent variable

- Specificity of association between an independent and the dependent variable through use of two-way analyses of two independent variables.

On the other hand, this method is quite laborious, calls for interposition of human judgment at every step of the analysis, and requires large amounts of valid data to test the statistical interaction of several variables. Because of these onerous requirements, the distribution-free method of analysis is used only when multivariate regression analysis is not applicable.

4. Impact of Cofactors and Covariates

A recurring theme throughout this chapter has been the impact of cofactors and covariates on definition of the dose-effect relationship. Cofactors are usually defined as factors that mimic or act in concert with air pollutants, whereas covariates may be thought of as factors that vary jointly with the principal variable. The distinction is obviously very fuzzy and the two terms do get used interchangeably.

The principal covariates in air pollution effect studies may be listed as follows:

- Other pollutants
- Meteorological conditions
  - Humidity
  - Temperature
  - Precipitation
  - Wind speed and turbulence
  - Mixing height
  - Sunlight
- Other exposure
  - Occupational
  - Residential (including smoking)
  - Influenza
- Personal characteristics
  - Age
  - Race
  - Sex
  - Genetic factors
  - General health

- Socioeconomic characteristics
  - Medical care
  - Nutrition
  - Exercise habits
  - Occupation
  - Income
  - Education
  - Housing
  - Population density
- Timing
  - Days of week, or month
  - Holidays
  - Seasons

An ideal investigation of the specific effects of an air pollutant would hold constant, or control all likely covariates. This can be accomplished, respectively, by judicious design of the investigation, or by statistical techniques. Personal and socioeconomic covariates may be held constant by employment of time-series investigations or selection of comparable populations in cross-sectional studies. All studies should discount seasonal and other temporal variations.

A good illustration of the statistical techniques is provided by a classic multivariate regression analysis of the association between mortality and air pollution, which controlled many of the covariates listed above (Lave and Seskin, 1973). One of the most serious problems was found to be multicollinearity, which occurs when some of the independent variables are so highly correlated with one another that it becomes nearly impossible to isolate and estimate their individual impacts. Techniques available to treat these difficulties include the use of principal components (Harman, 1967) and ridge regression (McDonald and Schwing, 1973), but their application is frequently accompanied by other undesirable features.

Unfortunately, in most cases, there are factors which elude control. Some of these are difficult to measure conceptually, while others suffer from poor availability of data. Other problems arise when there is a factor that is the actual cause of both a given air pollutant and its effect. This could be illustrated by the role of sulfur dioxide in the formation of ozone and damage to plants. Such a factor would give rise to a spurious correlation between the air pollutant and the effect being investigated (Simon, 1954).

F. PRESENTATION OF RESULTS

The utility of a dose-effect function is heavily dependent on the format and meaningfulness of its presentation. This last section takes up the types and quality of relationships encountered, selection of measures, and nature of errors and uncertainties.

1. Types of Dose-Effect Relationship

The classical representation of the relationship between exposure and effect takes the form of a sigmoid, or S-shaped curve shown in Figure 30. The ordinate may represent either the number of individuals affected or severity of effect. The abscissa indicates the dosage in terms of time at a given ambient concentration, or in terms of ambient concentration for a fixed period of time. The lower portion of the curve suggests that, up to a low exposure value, known as the threshold level, no effect has been observed. The upper portion indicates that there exists a saturation level (e.g., death of the target population or total destruction of the crops), beyond which increased exposure does not produce additional effect. The middle, quasi-linear portion is very useful in that any data points here can be readily interpolated, and the frequent assumption about linearity of a dose-effect function is most valid in this sector.

Nearly all the graphs of dose-effect functions reviewed in the course of this study represent some variation on this basic relationship. Most frequently, they involve the linear (Figures 3, 6, 7, 8, 9, 19, 22, 23) or curvilinear (Figures 14, 17, 20, 21, 24, 25, 28, 29) portions of the curve or some linear approximation (Figures 4, 11). A special case of the latter is known as a "hockey stick" function (Figure 31). Bar charts (Figures 5, 26) are more appropriate when exposure is expressed in terms of average values during changing intervals. Finally, effect can be expressed as a function of both concentration and exposure time, as well as several pollutants, or some cofactor of air pollution, with the aid of families of curves (Figures 8, 17, 20, 21, 24) or multi-dimensional plots (Figures 12, 13, 18).

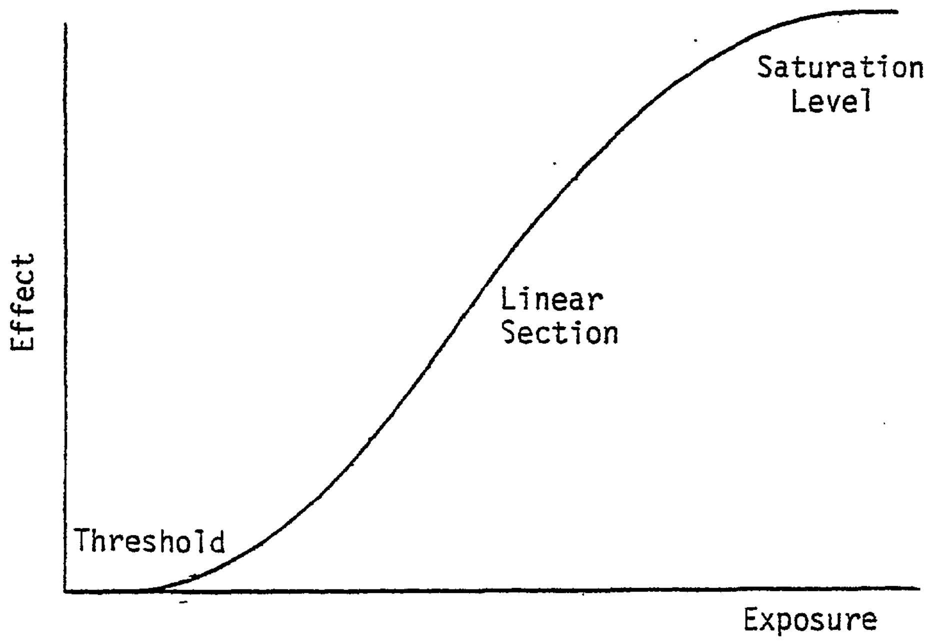
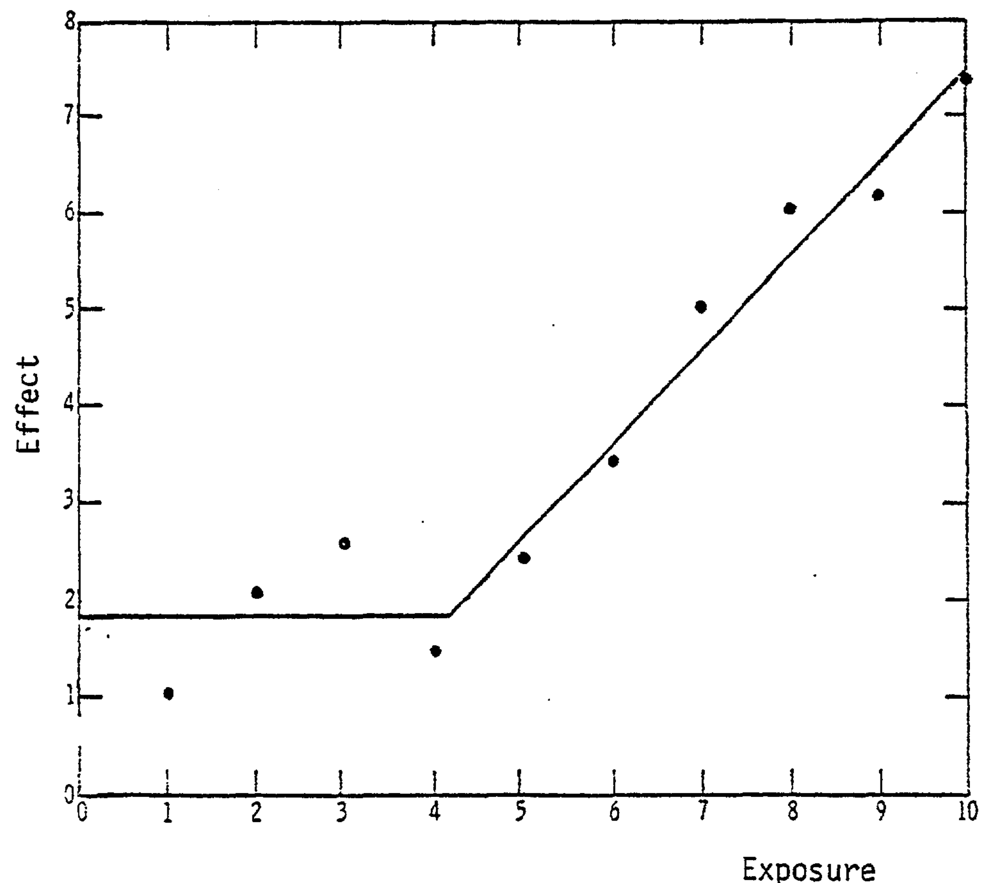


Figure 30. Hypothetical Dose-Effect Function



Source: Hasselbald *et al.*, 1974

Figure 31. "Hockey Stick" Curve Fitted to Artificial Data

Some representative mathematical formulations are presented in Table 22. It may be noticed that there is no consistent pattern for expressing these relationships.

Table 22. Selected Dose-Effect Relationships

Relationship	Definition of Terms	Reference
Health Effects		
$MR_i = a_0 + a_1P_i + a_2S_i + e_i$	MR_i = mortality rate for a particular disease in area i; P_i = measure of air pollution; S_i = measure af socioeconomic status; e_i = error term with zero mean	Lave and Seskin, 1972
EMR = 0.00339 C - 0.860	EMR = percent excess mortality; C = concentration of sulfur dioxide, $\mu g/m^3$	Buechley et al., 1973
Vegetation Effects		
$C = a + b_1I + b_2/T$	C = concentration; I = percentage of plant response; T = time; a = response threshold; b_1 = genetic resistance factor; b_2 = external resistance factor	Heck and Tingey, 1971
Material Effects		
CR = 0.001028 (RH - 48.8)C	CR = corrosion rate of zinc, $\mu m/yr$; RH = relative humidity; C = concentration of sulfur dioxide, $\mu g/m^3$	Haynie and Upham, 1970

2. Quality of the Relationship

The most general type of relationship between exposure and effect is termed "associative". This merely means that certain effects have been found associated with given levels of exposure of a population to a specific pollutant. Establishment of the more rigorous "causal" relationship requires the additional adducement of direct or indirect evidence of causation. In the case of human health effects, such direct evidence is difficult to obtain, and indirect evidence must be used. This is based primarily on a plausible mechanism and toxicological experiments using animals as surrogate subjects for humans. For vegetation and materials, controlled experiments can be conducted, showing that the effect occurs upon exposure to the given pollutant and does not occur when that pollutant is missing.

The evidentiary characteristics of a causal relationship include strength, specificity, and consistency. Strength of the relationship may be measured by the degree of correlation between exposure and effect. Specificity refers to whether only the given factor can produce the observed effects. Consistency is tested by any departure from the established functional relationship. The increasing degrees of certainty of a causal relationship may be expressed by such terms as "suggested", "possible", "likely", and "definite".

3. Selection of Measures

Measures of exposure and effects are characterized by a unit of measurement (e.g., $\mu g/m^3$, excess deaths per 10,000), a specific pollutant, a given effect, an instant or interval of time, a geographic location, and a population at risk (e.g., white males over 65, Bel W_3 tobacco). These concepts were discussed in some detail in the preceding sections. Results of dose-effect studies are usually reported in terms of some combinations of the various levels of aggregation of these parameters (e.g., annual means, SO_2, and smoke shade 140 SMSAs, respiratory diseases, white males). Selection of units of measure and combination of levels of aggregation should be governed by the need to accommodate the likely user, the intended use, and the available data.

Likely users of the information are public officials, businessmen, taxpayers, and exposed citizens. Obviously, any one individual is apt to find himself in more than one role. Public officials and exposed citizens are more likely to be interested in dose-effect functions and health effects, whereas businessmen and taxpayers would have more use for economic damage functions which attach a monetary value to the physical and biologic effects in all target areas.

Intended uses may take the form of national pollution control policy, establishment of air quality standards, planning of regional development, reaching of business decisions, and selection of place of employment and residence. It may be noted that the required level of geographic and population aggregation decreases as one moves down the list to the point where an individual making a personal decision may be interested only in the effects of a given exposure on himself and his immediate family.

Finally, certain desirable units of measure or levels of aggregation may not be obtainable because of lack of adequate resolution in the original data. For example, the daily excess mortality rates from chronic bronchitis, associated with daily means of SO_2 concentrations for white males over 65 obviously cannot be recovered from exposure data reported in monthly averages or from mortality rates that are not age or cause-specific.

4. Nature of Errors and Uncertainties

Errors in representing dose-effect functions may be characterized as errors of specification and measurement. The former include any type of error in specifying the functional form of the relationship under study or in accounting for important variables. A particularly common and grave error of specification is committed in attempting to extrapolate a complete functional relationship from a few data points that are barely adequate to characterize a small portion of the curve. Even if one were willing to make an assumption about the overall shape of the function, there is frequently no way of knowing which portion is represented by these data points.

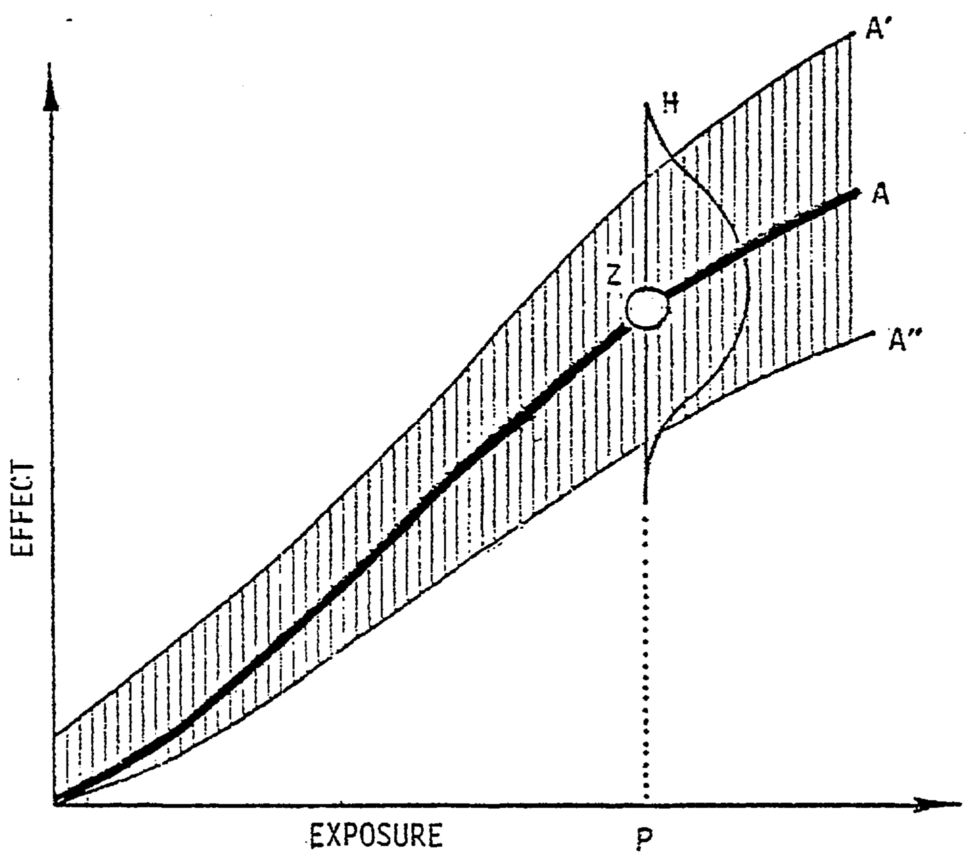
Errors of measurement have been alluded to throughout the several sections of this chapter and may be incurred in the course of the following steps and aspects of the development process:

- Ambient levels
  - Station location
  - Sampling
  - Analytical measurement
  - Averaging and aggregation of ambient levels
- Exposure
  - Location of subjects
  - Determination of exposure
- Effects
  - Determination of effect
  - Impact of cofactors, covariates, and mimics
  - Characterization of population at risk

If the errors of measurement of the independent variables are relatively small, occur at random, and follow a normal, or Gaussian distribution about the mean value of each variable, then the total error of all the independent variables can be computed by standard statistical techniques. This can then be compared to the error of measurement of the dependent variable (effect) to determine the overall uncertainty of the functional relationship between dose and effect, and of the estimated impact of the various covariates. However, this is seldom the case, because measurement of such independent variables as pollutant level, meteorological conditions, and socioeconomic characteristics is subject to errors that are both large and biased.

5.. Display of Uncertainties

The representation of errors of measurement and the ensuing uncertainties in the results is illustrated in Figure 32. Here, a point Z lying on the dose-effect curve A represents only the average or expected number of effects or affected subjects associated with



Source: Abel, 1974

Figure 32. Display of Uncertainty in Dose-Effect Function

exposure P. The actual measurements are characterized by some frequency distribution about point Z which, in the idealized Gaussian case, can be represented by curve H. If the variance of the points along curve A is known, then confidence limits can be calculated and represented by confidence bands A' and A".

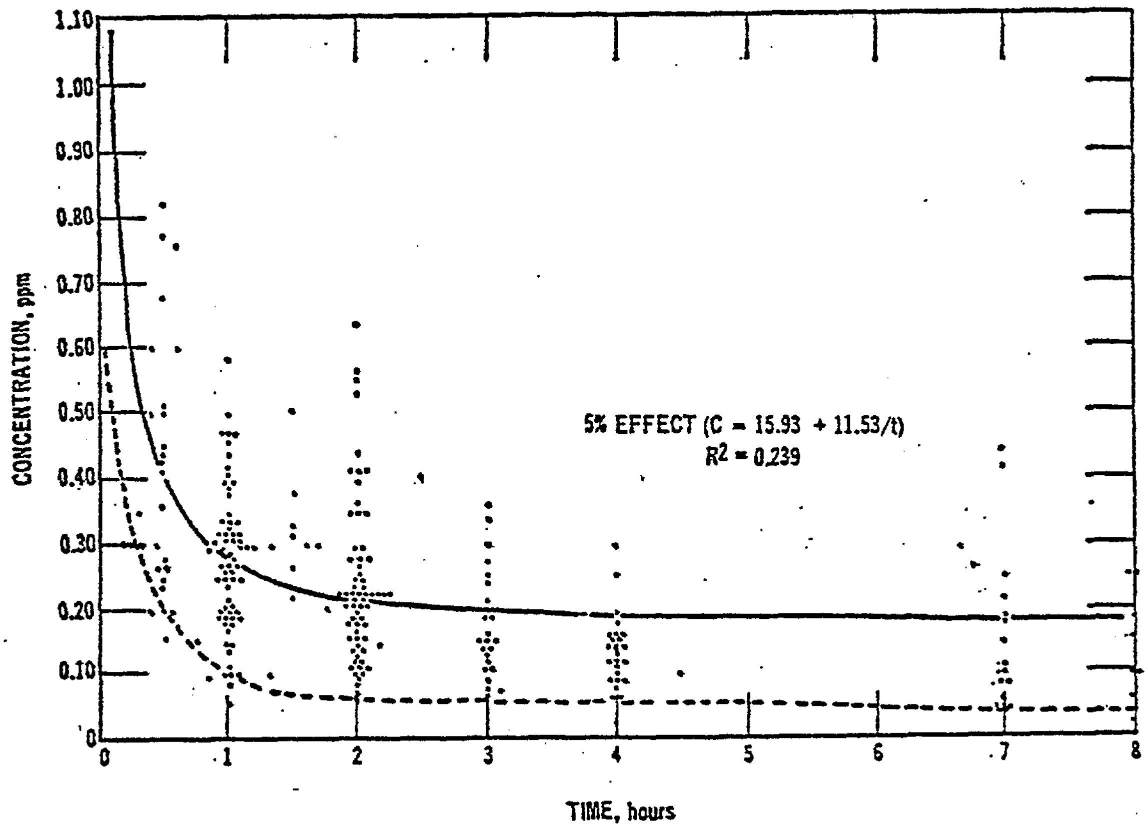
In actual practice, envelopes characterizing errors and uncertainties of dose-effect functions have been obtained by other means, including:

- Replicating a specific study with use of new data
- Manipulating values of the more important variables
- Combining results of several studies
- Applying "best" and "worst" case assumptions
- Bounding available data points.

Replication and data manipulation are essentially empirical techniques of determining the errors and corresponding confidence bands. Combining the results of several studies is a rare and uncertain opportunity, in light of the great variety of conditions and populations that characterize the different efforts (see Figure 33).

Application of 'best" and "worst" case assumptions is more an argumentative than a statistical technique. The lower boundary, or best case, is established by attributing all reasonable portions of the effect to any plausible cofactors and covariates and associating only the residual effects with pollutant exposure. The upper boundary, or worst case, is determined by inverting this procedure and assuming a minimal impact of other variables. (Finklea, 1973).

Bounding of data points by one or two boundary curves is indicated in cases where the data points are too scattered to justify plotting a simple curve. Such boundaries fall short of constituting a dose-effect function, but do provide some idea of the range of effect.



Source: NATO, 1974

Figure 33. Ozone Concentration Time Scatter Diagram of 5% Acute Plant Responses From Over 100 Species and Varieties Calculated From Data Taken From References; Dotted Line Approximates an Acute Response Threshold.

6. Merits and Failings

Properly constituted and qualified dose-effect functions can serve as valuable instruments in meeting the following intermediate objectives in the public decision-making process:

- Popular conceptualization of the threats posed by various levels of environmental pollution and the beneficial changes expected from pollution abatement.

- Planning of residential, commercial, and industrial development, including siting, transportation, and utilities

- Planning national and regional pollution control policy

- Establishment of environmental quality standards designed to protect public health and property.

Unfortunately, development of dose-effect functions has suffered from a number of failings which have necessarily limited their potential role. Among the most salient of these are:

- Insufficient data, requiring daring extrapolations of a curvilinear function from only a few data points

- Lack of proper representation of the uncertainty of the functional relationship

- Failure to account properly for the impact of other pertinent variables and for synergistic interactions among pollutants

- Attempt to represent complex and dynamic relationships by quasi-linear and static functions.

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IV. ANALYSIS OF SELECTED FUNCTIONS

This chapter provides an in-depth analysis of selected dose-effect functions to determine how they could be rendered more valid and useful to potential users. The first section is devoted to selection of three functions, whereas the remainder of the chapter contains the analyses of each function, based on the methodology discussed in the preceding chapter.

A. SELECTION OF FUNCTIONS

Dose-effect functions for in-depth analysis are selected here for each of the three major damage categories (health, vegetation, and materials) and two of the five major pollutants (particulates, sulfur dioxide, nitrogen dioxide, oxidants, and carbon monoxide), for which significant studies have been carried out on the basis of their relative importance and validity.

1. Selection Criteria

The impact of a dose-effect function on potential policy decisions may be determined by four criteria:

- Importance of effect
- Data quantity and compatibility
- Data quality
- Validity of function.

Importance of effect may be assessed in terms of the resulting loss to society. Quantity and compatibility of data are interrelated, because only data from compatible studies can be legitimately combined to expand the data base. The notion of compatibility encompasses exposure and effect indices, dose rate, target population, geographic area, and time frame. Data quality can be judged on the merits of their source, precision, and accuracy. Finally, function validity can be determined on the basis of how well the curve fits the data, the statistical methods used, and the validity of assumptions used in estimation of the functional relationship, as well as the consistency and plausibility of the observed association.

The relative weighting of each criterion in the selection process depends on the category of effects, specific objectives of the selection process, and the subjective considerations of the analyst. For example, in the area of human health, a function reporting the impact on mortality may be considered of overriding importance. In the area of vegetation damage, crop yield may be of more direct economic significance than leaf injury, though poor compatibility of the yield data might force the use of a narrow data base. In the materials area, there is little conflict between the economic importance of the effect and the size of the data base. This is probably due to the fact that material effects are more easily quantifiable from a physical and chemical standpoint.

Analytical considerations to be addressed during in-depth analysis of damage functions include:

- Measurement of ambient levels
- Determination of dose and dose rate
- Selection and aggregation of dose indices
- Determination of effects
- Selection and aggregation of effect indices
- Characterization of population-at-risk
- Validity of dose-effect relationship
- Characterization of errors and uncertainties
- Relation to criteria and standards
- Relation to other studies.

The damage functions selected are analyzed with respect to these considerations and resultant conclusions and the recommendations are formulated in the major sections that follow. The analysis is based on the methodology covered in the preceding chapter.

2. Selection Process

Major Air pollutants and their effects were listed in Table 1. The corresponding dose-effect functions that appear as likely candidates for in-depth analysis are presented in Table 23.

Table 23. Candidate Dose-Effect Categories for In-Depth Analysis

Area	Pollutant	Effect
Human Health	Sulfur oxides	Mortality
	Sulfur oxides	Respiratory illness
	Oxidants	Impairment of respiratory function
	Oxidants	Eye irritation
	Nitrogen oxides	Mortality
	Nitrogen oxides	Respiratory illness
	Carbon monoxide	Aggravation of heart disease
	Carbon monoxide	Behavior impairment
Vegetation	Sulfur oxides	General damage
	Oxidants	General damage
	Oxidants	Leaf injury
	Oxidants	Yield reduction
Materials	Particulates	Paint deterioration
	Sulfur oxides	Metals corrosion

All of the health effects listed rate highly under the importance criterion, with the possible exceptions of eye irritation and behavior impairment. Data quantity and quality for the first two health categories are satisfactory, although studies in the second category have been done for different geographic areas and population groups and may not be fully compatible. The effects of nitrogen oxides have not received adequate study. A good epidemiological and toxicological data base exists for the effects of oxidants and carbon monoxide.

The importance of effects of air pollutants on vegetation lies in the extent of damage which they may cause to the nation's agricultural crops valued at nearly $40 billion annually, as well as to the forests and ornamental plants. Oxidants are potentially the most damaging pollutants and the data base for oxidants is very extensive. However, the results of the many different studies are not compatible, because they were performed for different plant species and under varying conditions and exposures. For this reason, consideration of a specific genus, or at least type of plant, such as pine, citrus, or tobacco, would be more appropriate. A substantial data base has been generated for sulfur oxides as well. However, the effects of fluorides have been investigated less extensively, primarily because of their localized occurrence.

The pollutants implicated in damage to materials are primarily particulates and sulfur oxides. The data base is severely limited by the small number of studies, but the results of these are highly quantitative and cover a greater range of values than do studies in vegetation or health effects. The reason for this is the greater opportunity to conduct controlled laboratory tests of these effects. The effects of acute and chronic exposure of steel, zinc, copper, and aluminum to sulfur oxides have been investigated extensively, under both ambient and laboratory conditions. In the case of steel and zinc, studies have been conducted in both urban and rural locations. The only potential compatibility problems are those associated with use of currently disqualified air pollutant monitoring techniques and exposure of different alloys of these metals.

In light of all these considerations, the following three dose-effect functions were selected for in-depth analysis:

- Sulfur dioxide (or sulfates) - human mortality
- Ozone - injury to tobacco leaves
- Sulfur dioxide (or sulfates) - corrosion of zinc.

B. EFFECTS OF SULFUR DIOXIDE ON HUMAN MORTALITY

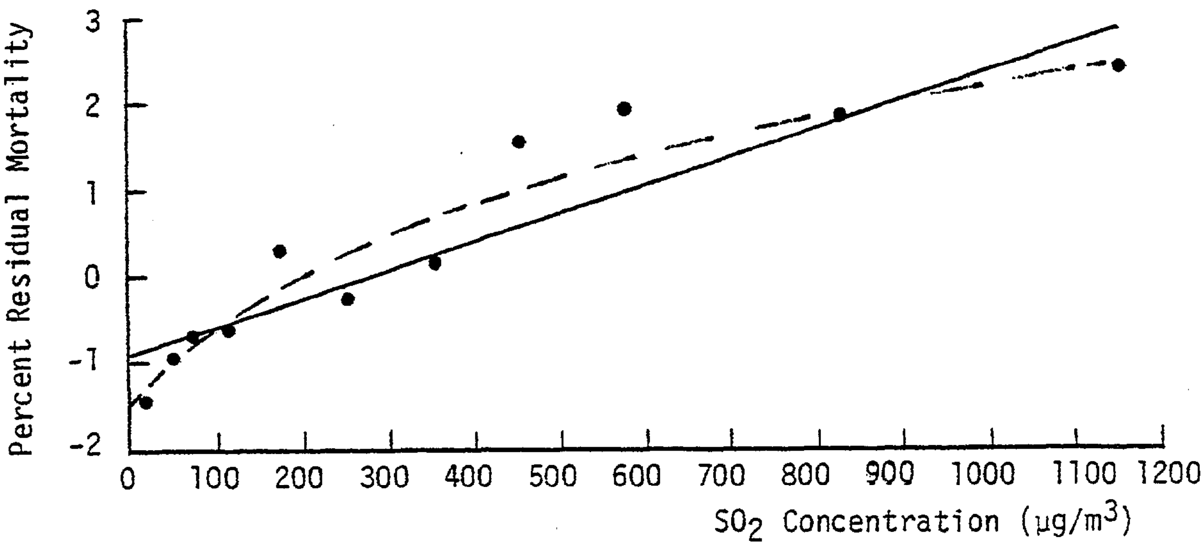
Effects of sulfur dioxide on human mortality represent the most intensively studied area of air pollution effects. The specific study analyzed here is among the best in this area. The analysis here follows the general outline formulated in Section A.

1. Description

The dose-effect function, selected to represent this pollutant-effect category was originally presented in 1972 at a Medical Research Conference and published a year later by Buechley et al., (1972, 1973). It established daily SO_2 concentration as a significant predictor of daily mortality in a large, densely populated, highly polluted metropolitan area. The function is shown in Figure 34 and may be expressed by the equation:

$$\text{Percent Residual Mortality} = 0.00339\ (SO_2,\ \mu g/m^3) - 0.860$$

The underlying data are displayed in Table 24.



Source: Based on Buechley, 1975

Figure 34. Relationship Between Daily Residual Mortality and Sulfur Dioxide Concentrations for the New York-New Jersey Metropolitan Area During 1962-1966; Solid and Dashed Plots Represent Two Possible Fits.

Table 24. Daily Sulfur Dioxide Concentrations and Daily Residual Mortalities for the New York - New Jersey Metropolitan Area During 1962-1966

SO_2 Concentration, in $\mu g/m^3$	Duration, in Days	Daily Mortality, As Percent Deviation From Mean
15 (0 - 30)	232	- 1.47
45 (30 - 60)	120	- 0.98
70 (60 - 80)	130	- 0.68
110 (80 - 140)	210	- 0.62
170 (140 - 200)	212	0.27
250 (200 - 300)	275	- 0.26
350 (300 - 400)	184	0.76
450 (400 - 500)	203	1.54
575 (500 - 650)	99	1.94
825 (650 - 1000)	114	1.85
1150 (7000 - 1300)	47	2.40

Source: Buechley, 7975

2. Determination of Exposure

The area covered by this study was approximately the New York-New Jersey-Connecticut air quality control region, with a 1960 population of 13,760,112. The measurements of air quality for the entire area were based on readings from only one air pollution monitoring station operated nearly continuously during the 1962-1966 period: the 121st Street Davis Laboratory in Manhattan. Gaps in the data were filled by reference to other stations, or by estimation. An analysis by Blade and Ferrand (1969) of 1957-1968 records for New York City shows that the Davis Laboratory observations were acceptably representative of readings for the area and especially of relative levels. This is not unexpected, because the entire area is replete with point and area sources of SO_2.

The specific measure of concentration was obtained by averaging hourly concentration readings over each 24-hour period. The resulting variable can be regarded as either an average concentration or a dosage, since all time periods were equal. Determination of dose (actual intake of pollutants), as distinct from dosage (opportunity to take in pollutants), is not important for the purpose of this study, because its task is to relate variations in ambient concentrations to health effects. The averaging process may conceal short concentration peaks and yield erroneous results for acute effects.

3. Determination of Effect

The population at risk was the entire population of the area and the measure of effect was total mortality. Buechley *et al.* (1973) had analyzed mortality data for 422 localities in the United States, and the New York study represented a subset of this study for which acceptable air quality records were available. The total number of deaths for the five-year period, after eliminating the effects of "disasters" and "time trends", was 754,219. A mean daily death rate of 413.04 was obtained by dividing this total by the number of days (1826). Finally, the observed deaths on a given day were divided by 413.04 to give the mortality ratio for that day. Cause-specific deaths were not considered, with the exception of influenza-pneumonia.

The determination of effect was flawed in several respects. First, by looking at daily averages, the study emphasized acute at the expense of chronic effects. Obviously, the mean daily death rate and the mortality ratio for any given day were the result of many years of exposure and their correlation with daily exposure can only represent the terminal step in that process. Conversely, the effect of an exposure on any given day is likely to be reflected in a death occurring years later.

Moreover, the study failed to account for individual differences in susceptibility among the various classes of the population at risk. The effects of SO_2 exposure would be expected to impact most severely on certain classes of the population, such as infants, the aged, heavy smokers, and sufferers from advanced pulmonary or cardiovascular disease. The function for these classes would almost certainly indicate a higher level of damage and a different slope. Such a refinement would have further validated the results of the study by noting whether effects follow the expected trend, and would have afforded useful additional information to potential users. A similar argument could be made for the desirability of specifying the cause of death.

4. Estimation of Dose-Effect Relationship

Multiple regression analysis was used to estimate the individual contributions of a number of variables to the mortality ratio. The following covariates were identified:

- Major covariates
  - Annual cycle
  - Extreme heat
- Intermediate covariate
  - Influenza epidemics
- Minor covariates
  - Warm and cold weather
  - Holidays (Christmas and New Year only)
  - Day of week
  - Sulfur dioxide
  - Coefficient of haze.

Other cofactors were tested without success.

With the other covariates controlled, sulfur dioxide was a significant predictor. Table 23 shows that mortality was 1.5 percent less than expected on 232 days with SO_2 concentrations below 30 $\mu g/m^3$, and 2 percent greater than expected on 260 days with SO_2 concentrations above 500 $\mu g/m^3$. However, the coefficient of haze and smoke for 7965-1966 did as well as SO_2 in predicting deaths.

The use of SO_2 concentration as the index of air quality does not imply a direct causal relationship with mortality. Toxicological evidence points to the fact that SO_2, acting alone at these levels, is no worse than a mild irritant. Other evidence indicates that sulfates, which may be formed from the SO_2, are much more toxic, that there exists an association between sulfates and mortality, and particulates can have a synergistic effect. It is, therefore, quite likely that, in showing an association with mortality, SO_2 measurements are acting as a proxy for sulfates, for SO_2 and particulates, or perhaps for some other species.

These considerations restrict the applicability of the damage function in locations, where the distribution of pollutants may differ significantly from that prevailing in the area under study. If the synergistic effect of SO_2 with particulate pollution is important, the function may not apply in areas of different particulate pollution level. Similarly, the rate of formation of sulfates and their precise composition are affected by environmental factors which differ from place to place. Finally, SO_2 is an adequate proxy for other pollutants only insofar as their relative emission rates and distributions are similar.

5. Display of Results

The data points in Figure 34 can be fitted reasonably well by a straight line, considering the limitations of the data base. However, an even better fit is a portion of the classic S-shaped curve, and in fact, the authors plotted the results as a logarithm of the dose vs. a linear measure of effect.

The form of the relationship at the lower concentrations is of special interest. The linear plot exhibits no threshold, which implies that benefits from reduced pollution continue down to zero concentration. This suggests that inducement of death through acute aggravation of morbid conditions may not be the typical damage mechanism and that the association of daily pollution into same-day mortality may have more complex antecedents.

6. Relationship to Other Studies

Glasser and Greenburg (1971) attempted to explain deviations in New York City's daily mortality from a five-year "normal" on the basis of sulfur dioxide and smoke shade as measures of air pollution, as well as a number of climatological variables. With the aid of a regression analysis, they found a definite relationship between daily mortality and air pollution, as measured primarily by sulfur dioxide. The analysis also included rainfall, wind speed, sky cover, and temperature deviations as explanatory variables.

In a study of New York City data between 1963 and 1968, Schimmel and Greenburg (1972) obtained a similar estimate of the SO_2 effect using slightly different analytic techniques. They concluded that there were 10,000 deaths per year (12 percent of all deaths) in New York City "which would not have occurred at the time they did if there had been no pollution on the day of death or immediately preceding days".

Lave and Seskin (1973) studied the relationship between mortality rates and a large array of environmental, biological, and socio-economic factors in 117 standard metropolitan statistical areas. They found a substantial correlation between suspended particulates and sulfates and mortality and concluded that a 10 percent reduction in each pollution measure would reduce the mortality rate by 0.9 percent.

A comprehensive U.S. EPA report observed that aggravation of symptoms has been repeatedly demonstrated at daily SO_2 levels well below the indicated threshold for excess mortality. Health consequences ranging from functional changes preceding disease to death itself have been associated with SO_2 exposures in the range of 80-120 $\mu g/m^3$ for one or more days. Daily sulfate levels in the 7-14 $\mu g/m^3$ range have been associated with aggravation of symptoms in particularly vulnerable population groups.

Finally, it should be noted that both Buechley and Schimmel are in the process of revising their estimates of the quantitative impact of pollution on mortality, which they now believe to be substantially less, though still significant (Buechley, 1975). This in no way affects the value of the dose-effect function developed by Buechley et al. as an illustration of analytical methods and of some typical strengths and limitations of such work.

The air quality criteria published by NAPCA (1969) and updated by NATO (1971) are based on epidemiological studies which indicate that mortality increases may be observed above 500 $\mu g/m^3$ (24-hour mean value) in the absence of heavy particulate pollution, and at values as low as 115 $\mu g/m^3$ in smoky air. The corresponding standards are a 24-hour mean of 365 $\mu g/m^3$ and an annual arithmetic mean of 80 $\mu g/m^3$.

In the present dose-effect function, a 24-hour mean of 365 $\mu g/m^3$ corresponds to an excess death rate of 0.4 percent with respect to the "normal" baseline.

An estimate of the annual mean corresponding to the 24-hour maximum value of 365 $\mu g/m^3$, based on New York City data for 1973, is 93 $\mu g/m^3$. This is in fair agreement with the annual mean standard of 80 $\mu g/m^3$. The function indicates that, if this standard had prevailed in the years 1962-1966, the residual mortality baseline would have been about 0.6 percent lower.

7. Conclusions and Recommendations

The foregoing analysis suggests the following conclusions:

- The dose-effect function shows a valid relationship between daily residual mortality and daily SO_2 concentration for New York City during 1962-1966, despite the limitations of the data base and analysis

- The most serious defects of the study (which were generally recognized by the investigators) are the single monitoring station and the use of a pollutant which is probably not the causal factor

- The function may be an acceptable predictor for other places and times, but its applicability would require environmental and population factors similar to those encountered during this study

- The function does not support the existence of a threshold

- Further developments along similar lines, with a more detailed classification of the population at risk and specification of the cause of death, are highly desirable.

Consequently, the following actions are recommended:

- Monitoring of SO_2, particulate, and sulfate levels at a sufficient number of stations to have a demonstrably representative measure of air quality

- Detailed analysis of the health effects as a function of exposure to sulfuric acid, acid and metal sulfates, and particle size

- Special attention to conditions at and below the national air quality standards

- Characterization of the population at risk, with emphasis on age, race, general health, smoking habits, and occupation

- Addition of other health-related damage functions, including aggravation of symptoms in chronically ill persons, impairment of lung function in healthy and ill persons, and contributions to the incidence of acute and chronic respiratory disease in various population subgroups

- Collection of cause-specific mortality data.

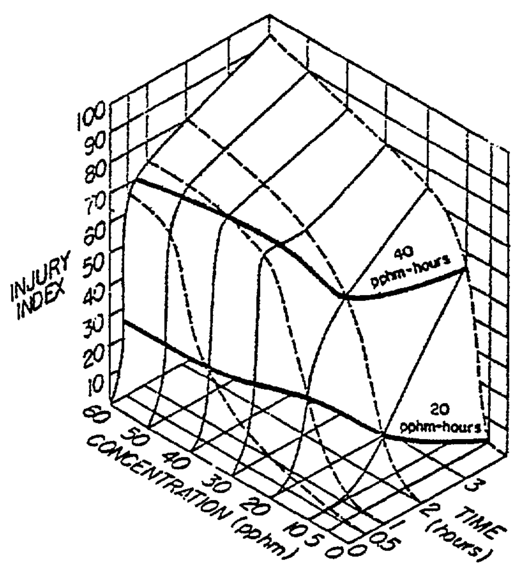
C. OXIDANT INJURY TO TOBACCO LEAVES

This section presents an in-depth analysis of the injury to tobacco leaves produced by elevated oxidant levels. The analysis follows the general outline formulated in Section A.

1. Description

Investigations designed to characterize injury to tobacco leaves by oxidants and related factors have been conducted by Heck et al. (1966), Menser and Heggestad (1966), Turner et al. (1972), Heagle and Heck (1974), and Taylor and Rich (1974). These studies were conducted under different exposures, experimental conditions, and measures of leaf injury, which makes it very difficult to reconcile the data or to integrate them into a self-consistent damage function.

The function selected for the present analysis was developed by Heck et al. (1966) for the Bel W-3 cultivar of tobacco (Nicotiana tabacum L.). The graph of the function, shown in Figure 35, provides a vivid demonstration of the different effects of the concentration and time elements of exposure on leaf injury, permitting the interpretation of both chronic and acute effects. Two equal-dose curves are indicated for 20 and 40 pphm-hrs.



Source: Heck et al., 1966

Figure 35. Relationship Between Oxidant Exposure and Injury to Bel W-3 Tobacco Leaf

2. Determination of Exposure

The plants were grown in controlled environment chambers approximating field conditions, including ozone levels, relative humidity, and temperature. Exposures were made at 0.1, 0.2, 0.3, and 0.55 ppm for periods of 1/2, 1, 2, and 4 hours. Each exposure was replicated four times, to produce the equivalent of four days' exposures, and administered to four plants, to achieve more representative results.

Ozone levels were measured with a coulometric MAST recorder which reads out the current necessary to maintain a constant halide concentration in a solution where the ozone has been absorbed. Within a certain range, the magnitude of the current is directly proportional to the amount of ozone absorbed. However, freshly generated ozone released and mixed with air may form other unmeasured and unreported oxidants, making the oxidant readings too low.

As was the case with health effects, it is not practical, nor even necessary to determine a dose that is distinct from the dosage, if experimental conditions remain basically the same or can be assumed to cancel out among populations. Differences between, these quantities are due to evapotranspiration, which forms a protective barrier, air movement past the leaf surface, which has the opposite effect, and relative humidity, which regulates the opening of the plant's stomata and may affect the plant's susceptibility as well.

The concentration element of exposure is expressed in parts per hundred million (pphm), the time - in average number of hours in each of four days, and exposure - as product of concentration and time, or pphm-hours. It must be assumed that the dosage was kept constant for the duration of each exposure by some regulatory mechanism. However, in field situations, dosage exhibits both hourly and daily fluctuations and average concentrations may represent a poor approximation. Moreover, Heagle and Heck (1974) have shown that various exposures to oxidants produce varying predispositions of the plant to greater injury from subsequent exposures.

3. Determination of Effects

The leaf injury was manifested in the form of flecks, which make the leaf undesirable, or unacceptable, as cigar wrapper. In this case, therefore, there exists a direct correlation between injury and damage, or economic loss. The injury is measured in terms of an index, which is presumably based on the fraction of the leaf surface covered by the flecks, but otherwise is not clearly defined.

The fleck injury to tobacco leaves by oxidants may be caused by induced chemical interactions in the palisade and mesophyll cells leading to accumulation of toxic substances, degradation of cell membranes, and/or disruption of enzyme production. Extensive injury can decrease substantially the plant's photosynthetic capacity and reduce its growth.

The effect index selected by Heck et al. is based presumably on the fraction of leaf surface area covered by the flecks. Other indices listed below provide a less subjective, though not necessarily more appropriate, measure of damage:

- Reduction of leaf growth rate
- Reduction of photosynthesis
- Reduction of stomatal conductance.

The last two indices reflect a similar measure, since gas exchange limitations in the stomata affect the photosynthetic process. Moreover, changes in the efficiency of energy utilization by the plant's metabolic processes may compensate for the loss of photosynthetic capacity to some extent. Thus, reduction in leaf growth rate appears to provide the optimal measure.

Although tobacco represents economically the seventh most important crop plant, the Bel W-3 cultivar is not a commercial variety, but a research strain with a high susceptibility to ozone.

Cultivars 6590 and Connecticut 49 are considered moderately sensitive, and cultivar 6524 is ozone tolerant. The study gives no indication of the variation in effects between different plants of the Bel W-3 variety. This variation can be due to genetic variability, different growth stages, and varying environmental conditions, such as soil characteristics and leaf microclimate.

4. Validity of Dose-Effect Relationship

The graph in Figure 35 lends an informative representation of the effect of the concentration and time elements of oxidant exposure on tobacco leaf injury. It provides a vivid demonstration that dosage alone is not a sufficient measure of exposure.

The validity of the specific damage function. presented as far as it goes, should be rather good, since it is based on results of controlled experiments. One major flaw, in light of recent indications of serious damage under these conditions, is the lack of long-term exposures to low concentrations under 10 pphm. A more definitive judgment would require information on variance of individual results for the different plants, as well as an analytical, or at least visual, measure of the fit of the curves with respect to the data points.

However, the extent to which this limited function represents the more general relationship between oxidant exposure and damage to tobacco is subject to all of the reservations expressed earlier, namely:

- Uncertain relationship between ozone measurements and oxidant concentration
- Failure to isolate the effects of meteorological factors
- Artificial flattening of concentration fluctuations
- Subjective measurement of damage
- Failure to characterize uncertainties.

The national primary and secondary air quality standard for photochemical oxidants is a one-hour maximum of 0.08 ppm not to be exceeded more than once per year. According to the meager data available, these standards are exceeded frequently in rural areas. The function suggests that this may cause substantial damage to the more sensitive varieties of tobacco.

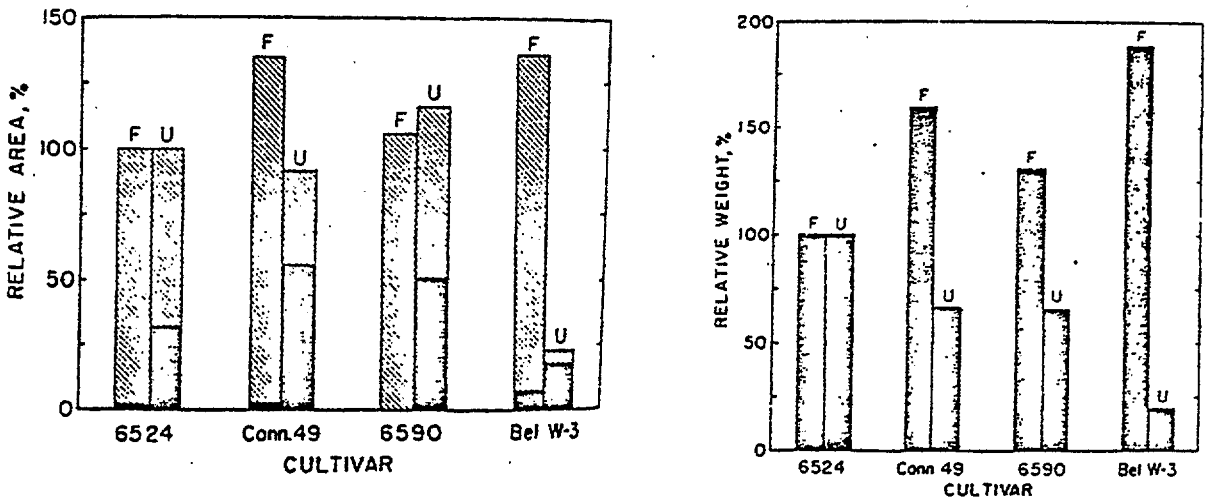
5. Relation to Other Studies

Other investigations of the relationship between oxidant exposure and injury to tobacco leaves were conducted by Menser and Heggestad (1963), Heagle and Heck (1974), Turner et al. (1972), and Taylor and Rich (1974), and covered the following topics:

- Synergistic effects of ozone and SO_2
- Predisposition of plant to ozone injury
- Comparative sensitivity of different varieties
- Effects of acute versus chronic exposure
- Protective measures against ozone exposure.

Menser and Heggestad (1966) reported a synergistic effect of sulfur dioxide with ozone, producing fleck symptoms. However, problems with the available measurement techniques at the time render their findings highly tentative. Heagle and Heck (1974) exposed tobacco plants to ozone during an eight week period and reported that exposure to ozone predisposes the plant to injury upon subsequent exposures, although it is not clear how this conclusion was reached on the basis of the reported data.

Turner et al. (1972) conducted exposure measurements in ambient and filtered (presumably ozone-free air) on four cultivars, including Bel W-3, over the entire season during a three year period. They found that, in filtered air, the ozone-sensitive Bel W-3 variety grew taller and heavier and had larger leaf area than the more ozone-tolerant varieties. In ambient air, on the other hand, the Bel W-3 variety had a significantly lower yield. With the leaf area decreasing and the amount of fleck injury increasing substantially in the unfiltered air, the resulting percentage of fleck injury for the Bel W-3 variety grew by a factor of nine from less than 10 percent in filtered air to more than 80 percent in unfiltered air. When reduction in leaf area is factored in once again to determine the total amount of usable leaf area, the total damage is assessed at 96 percent. This is illustrated in Figure 36.



Source: Turner et al., 1972

Figure 36. Comparison of Leaf Area (left) and Dry Weight (right) of Several Tobacco Cultivars in Filtered (F) and Unfiltered (U) Air

The dosages to which the plants were exposed in the previous experiments during the two growing seasons can be determined, with the aid of available data on prevailing ambient oxidant levels, at 7.75 and 8.25 ppm-hours, respectively. However, Heck et al. (1966) showed that an equivalent damage could be produced by an acute exposure for four hours to a concentration of 0.6 ppm, for a total dosage of 2.4 ppm-hours. This indicates that an acute dosage can produce the same damage as a much larger chronic dosage and that significant damage can occur over a growing season even at ambient levels below the national air quality standard.

Finally, Taylor and Rich (1974) measured the reduction of ozone injury to tobacco resulting from treatment of the plant with systemic fungicides. Leaf fleck was measured two days after high peak ozone concentrations on both treated and untreated plants. The fungicide treatment was found to reduce fleck damage by 77 percent, although stomatal openings were not affected.

6. Conclusions and Recommendations

Without doubt, the major problem with this entire area of inquiry is the lack of coordination among the individual efforts. With disparate objectives, experimental conditions, pollutant and effect measurement techniques, and reporting styles, it becomes exceedingly difficult and frustrating to draw any comprehensive and valid conclusions which are necessary to assess total economic damages and undertake judicious corrective action. This lack of a centralized guidance and coordination appears responsible for most of the flaws explored in the preceding sections.

In spite of these shortcomings, the damage function developed by Heck *et al*. can be very. useful in its present form and as a basis for additional research. Specific merits are listed below:

- Demonstrates a valid quantitative relationship between various exposures to oxidant levels and injury to Bel W-3 tobacco leaves
- Provides a vivid graphic illustration of the relative effects of acute and chronic exposures
- Served as a starting point for additional investigations which will eventually provide a quantitative characterization of the relationship between ozone exposure and tobacco injury and yield loss.

Consequently, the following actions are recommended:

- Establishment of guidelines and criteria for conducting research on effects of air pollutants on vegetation
- Collection of more complete data on oxidant levels in rural areas
- Development of more precise and appropriate damage measurement techniques
- Definition of the synergistic effects of pollutants, such as ozone and SO_2 and meteorological factors
- Discussion of the experimental assumptions and uncertainties in the results.

D. EFFECT OF SULFUR DIOXIDE ON CORROSION OF ZINC

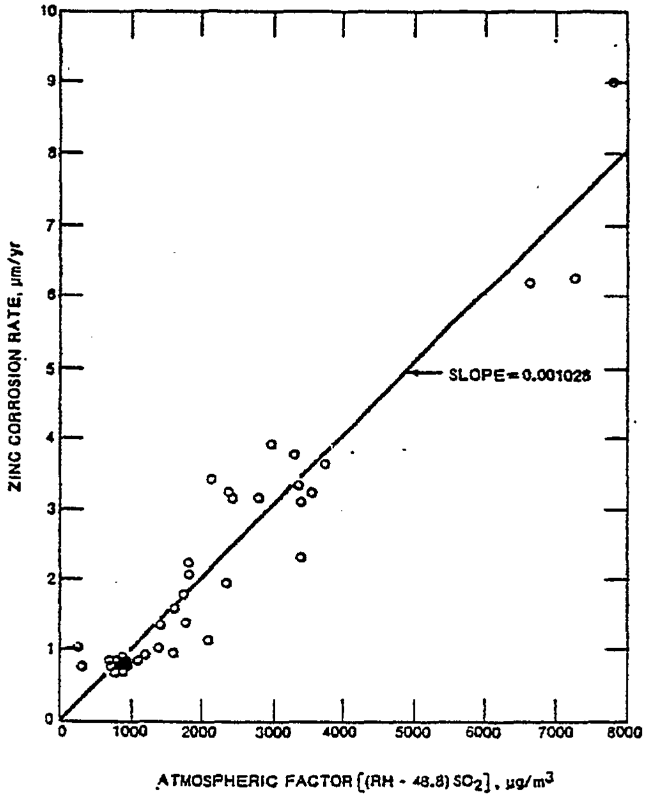
This last section analyzes the relationships between sulfur dioxide and humidity levels, on one hand, and the corrosion rate of zinc, on the other. The analysis follows the standard outline formulated in Section A.

1. Description

The importance of zinc lies primarily in its use as a coating for steel to help resist corrosion. The coating may be applied through hot dipping (galvanization) as electroplating. Corrosion of zinc and zinc-coated products accounts for a national annual loss of nearly $1 billion. A dose-effect function for zinc-coated steel would have a definite threshold up to an exposure level corresponding to the breaching of the zinc layer, whereupon the dose-effect function for steel would govern the relationship.

The damage function selected here was developed by Haynie and Upham (1970), from results of a series of controlled experiments in eight cities over a period of up to 64 months (see Figure 37). It expresses a linear relationship between an atmospheric factor composed of SO_2 concentration and relative humidity, on one hand, and corrosion rate of zinc, in micrometers per year ($\mu m/yr$), on the other. The authors conclude that SO_2 is a major cause of zinc corrosion in a non-marine environment and that a relative humidity in excess of a value just under 50 percent is required before SO_2 attack can become effective.

The experimental procedure may be outlined as follows. Small panels of high grade 0.06 inch zinc sheet were cleaned, weighed, and exposed to ambient air. Five groups of five panels each were exposed to periods of 4, 8, 16, 32, and 64 months, in Chicago, Cincinnati, Detroit, Los Angeles, New Orleans, Philadelphia, San Francisco, and Washington. Following exposure, the panels were cleaned to remove corrosion products and weighed again to determine weight loss. The latter was then converted to corrosion rate by applying a conversion factor and dividing by exposure time.



Source: Haynie and Upham, 1970

Figure 37. Relationship Between SO_2 and Relative Humidity and the Corrosion Rate of Zinc

2. Determination of Exposure

In the case of materials damage, the distinction between dose and dosage is moot since no protective mechanisms are in operation. Moreover, the dose rate was determined not to be important for these long exposure periods by comparing results from different cities, with varying concentrations. Thus, the time factor could be incorporated in the corrosion rate, the dependent variable.

The eight urban exposure sites were generally located near the Federal Continuous Air Monitoring Program (CAMP) stations, or their state or local equivalents, and SO_2 data were obtained from these stations. The SO_2 measurement techniques at the CAMP stations were not specified in the report, but those in common use today are the calorimetric gas bubbler employing pararosaniline-sulfamic acid, for daily levels, and a conductance meter, for the hourly values. Concentrations reported in ppm were converted to $\mu g/m^3$ by applying a conversion factor of 2620 which holds approximately at 25°C.

Relative humidity above 48.8 percent was found to be a major factor in the damage produced, while temperature did not contribute substantially. The authors observed that these findings are consistent with the concept of a reaction rate controlled by the diffusion of a low concentration species to the reaction site. Relative humidity data were obtained from the weather station nearest to each exposure site.

The SO_2 concentration and relative humidity were combined into an atmospheric factor expressed as SO_2 (RH - 48.8), where SO_2 is the concentration of SO_2 in $\mu g/m^3$ and RH is the percent relative humidity. The atmospheric factor does not reflect the likely effect of sulfates, but as long as the SO_2/sulfate section remains invariate, SO_2 concentration can serve as a proxy for both compounds.

3. Determination of Effect

Corrosion of zinc by SO_2 and moisture appears to take place with the breakdown of the protective carbonate film, diffusion to the reaction site, and reaction with the metal to form a soluble zinc sulfate, which was washed away.

The effect was measured in terms of weight loss in grams, which was related to loss of thickness in micrometers by applying a conversion factor of 4.4 $\mu m/g$. This permits the calculation of the useful lifetime of the 53 μm zinc coating, and hence, of the coated product. The national air quality standard for sulfur dioxide is an annual arithmetic mean of 80 $\mu g/m^3$. Assuming a typical relative humidity of 65 percent, this yields an atmospheric factor of approximately 1300, which corresponds to a corrosion rate of 1.3 μm/year, or a coating lifetime of 40 years.

The investigators provided sufficient replications in each exposure group to determine variance among individual samples. However, there was no indication how representative the zinc sheet used in the experiment was of the total population of zinc sheet and, more importantly, of zinc coating. Zinc coating would surely behave differently than zinc sheet, due to a different crystal structure and galvanic effects at the zinc-steel interface.

4. Validity of the Dose-Effect Relationship

The damage function in Figure 37 was derived as a simplication of one proposed by Guttman (1968). His formulation was

$$Y = k(RH-RH_0)(SO_2+B),$$

where,

Y = zinc corrosion rate
RH = average relative humidity
SO_2 = average sulfur dioxide concentration
k = proportionality constant
RH_0 = threshold relative humidity below which no corrosion occurs
B = factor providing for corrosion in the absence of SO_2.

Upon being arranged for multiple regression the equation becomes

$$Y = b_0 RH \times SO_2 + b_1 RH + b_2 SO_2 + b_3,$$

where $b_0 = k$, $b_1 = kB$, $b_2 = -kRH_0$, and $b_3 = -kBRH_0$.

Results of the regression analysis show that, at the 99 percent confidence level, only SO_2 concentration and SO_2 interacting with relative humidity are statistically significant. Factoring the equation into SO_2-dependent and independent terms in the form of

$$Y = .00104(RH-49.4)SO_2 - .00664(RH-76.5)$$

makes this more obvious. Here it can be seen that for normal relative humidities in the range of 50-80 percent the magnitude of the last term is 0.2 or less, which can be generally considered negligible, when compared to the SO_2-dependent terms.

A second multiple regression using only the SO_2 dependent terms was performed on the equation

$$Y = b_0 RH \times SO_2 + b_1 SO_2$$

This step produced the atmospheric factor of $[(RH-48.8)SO_2]$ which is directly proportional to the corrosion rate.

The authors state that this simple relationship accounts for 92 percent of the variability of the average corrosion rates and that the more complex equation given by Guttman does not yield a better fit. Our own analysis bears out the fit of the linear equation, yielding an r-value of 0.96.

The general range of the data, and hence of the damage function, is good, because it spans both the national standard and prevalent ambient values. This permits valid interpolation of most information of potential value.

The major errors of measurement are associated with SO_2 measurements at the CAMP stations and relationship between those values and ambient levels at the exposure sites. Unfortunately, neither component error is known. Measurements of relative humidity, exposure times, and corrosion rate are considered quite accurate.

5. Relation To Other Studies

Other investigations of the relationship between sulfur dioxide levels and the corrosion rate of zinc were conducted by Guttman (1968) and Dunbar (1968), covering the effects of wetness and differential sensitivity of different grades of zinc.

Guttman (1968) was the first to report that sulfur dioxide, relative humidity, and to some extent, temperature affected corrosion of rolled zinc and laid the foundation for the Haynie and Upham study. The experimental procedure involved measurement of the time of wetness of exposed panels using a dew detector. The results showed a correlation between time of wetness and corrosion rate. Dunbar (1968) tested three grades of zinc ranging in purity from 99 to 99.99 percent and found no significant difference in weight loss at any exposure site. This suggests that the damage function in Figure 37 holds for a wide range of zinc grades, although not necessarily for zinc coatings.

Haynie and Upham (1971) investigated the corrosion rate of steel at the same site used in the zinc survey. They measured grades up to 40 pm/year, or five times the highest rate observed in the case of zinc. This substantiates their assertion that the useful life of galvanized steel ends when the zinc coating has been beached.

6. Conclusions and Recommendations

Characterization of the relationship between pollutant levels and materials damage is devoid of many of the problems that plague similar efforts in the human health and vegetation damage areas. These include the relationship between dose and dosage, control of experimental conditions, and a complex characterization of the population at risk. Some of the problems, however, remain. Thus, the damage function developed by Haynie and Upham is simple, well defined, valid, and potentially very useful. Its only major flaws are the failure to characterize the error in measurement of SO_2 levels and the relationship between corrosion rate of zinc sheet, zinc coating an steel, and uncoated steel.

Indeed, the only likely recommendations for improvement deal with these two flaws:

- Characterize errors in measurement of SO_2 levels
- Conduct a less extensive series of tests on zinc-coated steel in parallel with zinc sheet to determine the relative corrosion rates.

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V. RESEARCH NEEDS

This final chapter delineates a limited number of suggestions for additional research that were culled from the material presented in the preceding chapters. These suggestions pertain exclusively to development of dose-effect functions and do not deal with such other related and interesting topics as improvements in air quality monitoring and modeling techniques or better understanding of effect mechanisms. Successive sections address methodological improvements in determination of exposure and effect and additional dose-effect studies. Each suggestion takes the form of a brief discussion of its objectives and means of implementation.

A. DETERMINATION OF EXPOSURE

Research needs explored in this section deal with improvements in determining exposure levels and in their representation.

1. Determination of Exposure Levels

The air quality of many communities is represented by one or only a few monitoring stations. This introduces a large error in the determination of exposure levels of the target population. Additional uncertainties are brought to bear by the mobility and shielding of human subjects. The objectives of this suggestion are to:

- Determine how well air quality measurements at a monitoring station represent the ambient quality in the surrounding community

- Determine the impact of mobility and shielding of the subjects on their exposure.

These objectives could be met with the aid of a mobile monitoring station that would measure pollutant concentrations at various outdoor and indoor locations, under different emission regimes and meteorological conditions. More refined measurements might be obtainable in some cases through the use of personal monitors. Some investigations of indoor air quality have already been conducted (Yocum, et al., 1971; Wade, et al., 1974).

Fulfillment of the second objective would also require calculation of a distribution of time spent outdoors for each class of the population at risk. The results of these efforts would appear in the form of confidence limits placed around specific sets of air quality data.

2. Representation of Exposure Levels

Inasmuch as most observed effects can be attributed to both long-term, low-level exposure and short-term peak concentrations, it appears reasonable that the index of exposure should account for both types of exposure. Thus, the objectives of this research suggestion are to:

- Develop an improved measure of exposure

- Explore the feasibility of translating different measures of exposure.

To this end, one could formulate a composite exposure index, such as

$$I = a + a_1 C_1 + a_2 C_2 + a_3 D$$

where a, a_1, a_2, and a_3 are empirically determined coefficients, C_1 and C_2 are the fractions of hours during which concentration exceeds some designated levels 1 and 2 (perhaps the primary and secondary air quality standards), respectively, and D is dosage, or the integral of concentration as a function of time.

The first phase of the suggested research would consist of replacing current exposure indices in dose-effect studies, for which adequate exposure data are available, with a composite index of the form shown above to determine whether this leads to an improved dose-effect function. Next, the accumulated knowledge would be used to explore ways of converting from one type of measure to another under different emission regimes and meteorological conditions. Such conversions would be very useful in cases where only one type of measure is available.

3. Define Monitoring Requirements

The selection of dose-effect studies today is governed at least as much by the availability of air quality data as by social needs. This is due largely to a lack of foresight by those responsible for planning and funding data collection programs. The objective of this suggestion is to remedy this situation by defining current air quality monitoring requirements for potential future dose-effect studies.

This effort would involve projection of all substantial future emission levels of likely hazardous pollutants and an estimate of the accuracy and specificity requirements dictated by future social needs and other uncertainties in the dose-effect relationships.

B. DETERMINATION OF EFFECT

Here, we take up research needs for determining the effects of air pollutants on human health and vegetation.

1. Determination of Morbidity

Morbidity in epidemiological studies is generally measured with the aid of hospital admission and occupancy and medical visit records, absenteeism from work and shcool, and personal diaries. The latter are considered the most accurate, but too costly and time consuming for massive studies.

The objectives of the proposed research effort would be to assess and improve the accuracy and reliability of the various methods for determining morbidity in dose-effect studies. This would be accomplished by comparing the data obtained by other means with those obtained from personal diaries for the same population to identify principal weaknesses and problems. The results of this effort would take the form of recommendations for improvements in the recording and collection of morbidity data.

2. Determination of Mortality

Mortality in epidemiological studies is expressed in terms of changes in the daily or annual death rate. However, it is not clear what this measure represents, because there is no way of knowing whether those individuals who appear to have died prematurely would have lived only a few days or many years in the absence of the pollution. The erratic behavior of mortality curves following periods of high pollution only serve to accentuate this uncertainty.

The proposed research effort would explore instead the feasibility of determining changes in life expectancy by comparing ages at death of age-adjusted populations exposed to different levels of air pollutants. As in other valid epidemiological studies, all other important covariates would have to be carefully controlled as well. The ultimate results of such an effort would be a demonstrated method for determining changes in life expectancy associated with exposure to a given pollutant for a well-characterized population group. (Takacs, 1974.)

3. Effects on Vegetation

Studies of effects of air pollutants on vegetation are characterized by a wide array of measures of effects. This frustrates any attempts at aggregating results of different studies over pollutants, plant species, geographic regions, or effects, and hampers the drawing of general conclusions about the dose-effect relationships.

The objective of the proposed effort would be to provide uniform guidance for experiment design, data collection, control of cofactors, measurement of effects, and display of results and the associated uncertainties. Such a study would obviously require the participation and endorsement of a wide spectrum of respected investigators in this field.

C. STUDY DESIGN

There are a number of lively controversies surrounding the design and development of dose-effect functions. Several of the more important are taken up below.

1. Cost-Effectiveness of Epidemiological Studies

In light of the large uncertainties characterizing the results of epidemiological studies, some people have suggested their replacement by more precise, though also much more costly, efforts. One such suggestion is Lester Lave's "dream study," which would focus on carefully selected sample populations in a number of cities. The selected individuals would be monitored to determine their personal exposure to all important environmental factors, including air pollutants, radiation, and weather conditions, and they would keep diaries recording their symptoms. (Morris and Morgan, 1974.)

The objective of the proposed project would be to assess the relative cost effectiveness of an epidemiological study and Lave's "dream study" for the more important pollutants and effects. Such an effort would need to take into account the timing and accuracy requirements of the intended uses of the results and would specify the conditions when one type of study is preferable to the other.

2. Estimation of Dose-Effect Relationships

A number of dose-effect studies have been excluded from consideration in our survey of the literature in Chapter II because of various flaws ranging from insufficient data to inadequate consideration of covariates, or use of improper statistical methods. This proposed research project would attempt to correct this situation by providing a manual for estimating dose-effect relationships.

Such a manual would define the preferred and optional statistical procedures to be followed for various sets of constraints and requirements. It would specify various methods of presentation of results and the associated errors and uncertainties. In effect, the manual would constitute a greatly expanded, reorganized, and more scholarly version of our Chapter III.

D. ADDITIONAL DOSE-EFFECT STUDIES

In addition to the methodological research needs outlined in the preceding sections, a number of important dose-effect functions still remain to be developed. These are defined here for the three major target areas.

1. Health Effects

The more important air pollution dose-effect relationships that need to be developed or validated may be listed as follows:

- Effects of NO_2 and nitrates
- Effects of different types of sulfates (e.g., metal, acid, salts)
- Chronic effects of low-level (below standards) exposures to various pollutants

- Carcinogenic, teratogenic, and mutagenic effects of air pollutants, as specified in Section 103(f)(2)(B) of the Clean Air Act of 1970.

2. Effects on Vegetation

Effects of air pollutants on vegetation appear much more widespread than had been heretofore suspected, especially in light of the recent discovery of high oxidant levels in rural, crop-growing areas. Yet past studies of growth reduction and yield loss exhibit widely varying results. Consequently, the following types of dose-effect relationships appear to be urgently needed.

- Effects of oxidants on yields of major crops
- Synergistic effects of sulfur oxides and oxidants
- Long-term effects of pollutants on ecological balance.

3. Other Effects

Other areas that deserve additional study are:

- Effects of various air pollutants on paints, cement, rubber, plastics and wood
- Effects of various air pollutants on aesthetic appreciation of an area, including visibility
- Effects of various air pollutants on climate and local weather conditions.

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APPENDIX

DEMONSTRATION OF THE INTERPRETIVE UTILITY OF AIR POLLUTION DAMAGE FUNCTIONS

APPENDIX. DEMONSTRATION OF THE INTERPRETIVE UTILITY OF AIR POLLUTION DAMAGE FUNCTIONS

This appendix contains a brief demonstration of specific uses of damage functions, prepared for inclusion in the Environmental Conditions and Trends Chapter of the CEQ 1975 Annual Report. The primary objective is to show how air pollution damage functions can serve as interpretive aids in communicating the significance of recently measured air quality trends to persons who lack advanced technical training.

The report begins with an introduction to the concepts of pollution damages and benefits, the nature of air quality trends, and the application of damage functions. The remainder of the presentation. takes up the utility of three damage functions and their relationship to air quality trends. These functions define the impact of sulfur dioxide on human health, oxidant injury to tobacco leaves, and effect of sulfur dioxide on corrosion of zinc.

A. INTRODUCTION

This section introduces the concepts of damages and benefits associated with environmental pollution, as well as the nature of air quality trends and utility of damage functions. The actual demonstration of the utility of several damage functions is taken up next.

1. Environmental Damages and Benefits

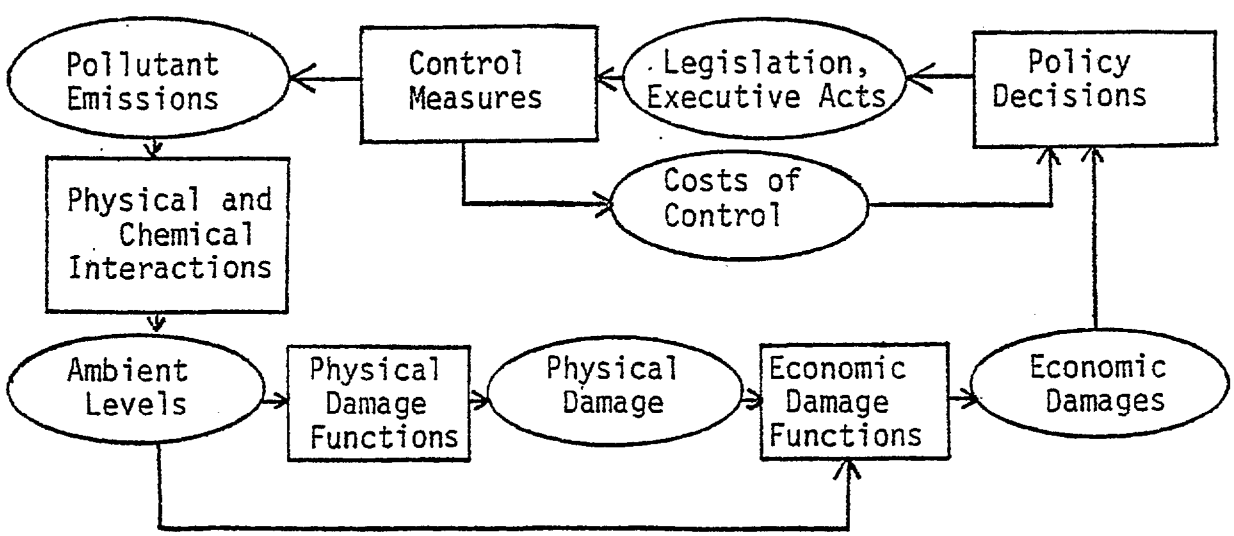
Nearly everyone is now convinced that there exists a causal relationship between environmental pollution levels and certain damages suffered by society. These may take the form of increased mortality and incidence, and prevalence of disease, diminished enjoyment of the outdoors, reduced crop yields, more frequent maintenance and replacement of exposed materials, and other, less well-identified losses. This being the case, a reduction in pollution levels should bring about a corresponding decrease in these damages and yield a set of benefits equivalent to the difference in damages before and after the reduction took place. If the damages are reduced to the point at which they are no longer observed, then the benefits realized are equal to observed damages.

Legislators, planning officials, and other environmental decision makers are frequently faced with the decision of how much to reduce pollutant levels in the light of the associated direct costs of pollution control and possible secondary economic effects. In the past, these decisions were rather obvious and they were made in response to popular sentiment. However, with the passing of time, these costs became more acutely felt, especially in the wake of the energy crisis, while the beneficial effects of reduced, or at least stable, pollution levels were neither obvious, nor easily measured. Clearly, the decision makers would need a more sensitive tool for comparing and trading off the costs and benefits of various levels and types of pollution control. Indeed, this need gave birth to the science of environmental benefit/cost analysis.

Admittedly, benefit/cost analysis is not an exact science, primarily because social benefits and costs are diffuse and frequently difficult to express in monetary terms. Even so, the process of logical and systematic scrutiny inherent in benefit/cost analysis can contribute substantially to the ability of decision makers to improve the social welfare through more efficient allocation of the limited resources of the public treasury.

There is an interactive relationship among pollutant emissions, ambient air quality, damages and benefits, and policy decisions. This is illustrated in the diagram below, where rectangles indicate processes and actions, whereas ellipses represent their products. The pollutants emitted by stacks, automobile exhaust pipes, and other sources undergo physical and chemical interaction in the atmosphere under the influence of meteorological factors to yield prevailing ambient pollutant levels. The resulting physical or biological damages are converted into some realistic economic terms and traded off against the costs of controls to guide decision makers on the extent and type of controls to be applied. Alternatively, economic damages can be determined directly as a function of ambient levels through surveys of property values, declared willingness to pay, legislative decisions, and litigation awards.

This is an adaptive process, with major decisions made at first on the basis of fragmentary information and successive refinements applied, as the constraints and implications of each step become better known. The transition between pollutant emissions and resulting damages is of special interest here and is taken up in more detail in the next two sections.



2. Ambient Levels and Trends

As was mentioned earlier, ambient pollutant levels are determined by physical and chemical interactions of pollutant emissions in the atmosphere under the influence of such meteorological factors as wind, precipitation, sunlight, and temperature. The most important mechanisms are dispersion and dilution of pollutants by air movement, as well as the formation of photochemical oxidants by various combinations of pollutants, including nitrogen dioxide and hydrocarbons, under the influence of the sun's ultraviolet radiation. Other important interactions with meteorological factors result in the oxidation of sulfur dioxide and nitrogen dioxide to the more hazardous sulfates and to nitrates, respectively, the entrapment of pollutants near the earth's surface by thermal inversions, and the cleansing of the air by falling rain drops.

Attempts to predict ambient levels on the basis of the nature and location of pollutant emissions and analytical models of the various physical and chemical interactions have been only partially successful. Consequently, many investigators have chosen to rely on measured ambient levels, or more recently, on air quality trends. These trends express the magnitude and direction of change in ambient levels of specific pollutants as a function of time, and they have several important advantages over measurement of ambient levels. In the first place, they provide the only valid indicator of the relative success of pollution control action, as well as some predictive measure of future damages associated with various levels of exposure to specific pollutants. Secondly, they tend to be more reliable than ambient measurements, because some errors of measurement may cancel out.

Comprehensive assessment of national air quality trends has become feasible only recently, in the wake of the requirement by the Clean Air Act of 1970 that each state collect and report specific air quality data. Air quality data for the five air quality standard pollutants (total suspended particulates, sulfur dioxide, carbon monoxide, oxidants, and nitrogen dioxide) are supplied by Federal, state, and a number of local agencies to the EPA National Aerometric Data Bank (NADB), where they are validated and consolidated. With the aid of these data, the EPA Office of Air Quality Planning and Standards has been able to publish in August 1973 the first annual Air Quality and Emissions Trends report, which analyzed nationwide emission trends between 1940 - 1971, and trends in ambient levels for more recent years. This document was subsequently supplemented by the 1972 and 1973 editions of Monitoring and Air Quality Trends Report, published in December 1973, and October 1974, respectively, which focused on recent ambient level trends for the nation's 247 air quality control regions. These reports concluded that ambient levels of sulfur dioxide, total suspended particulates, and other pollutants in urban areas have been decreasing in response to pollution control measures.

However, any interpretation of ambient level measurements, and hence of air quality trends, needs to be tempered by an appreciation for the serious limitations of present data collection practices. These may take the form of number and location of monitoring stations, measuring instrumentation, and data collection and processing. The location of air quality monitoring stations is somewhat erratic and is frequently dictated by expediency and convenience, rather than by the more fundamental considerations of proximity to pollution sources, meteorological patterns, or target populations. Moreover, a number of urban and most rural areas have insufficient coverage for specific pollutants, such as nitrogen dioxide or oxidants. This is especially troublesome in light of the recent discovery of high oxidant levels in rural areas and the resultant effects on crop yield.

Even more importantly, there are currently no direct and specific methods for measuring such important pollutants as nitrogen dioxide, nitrates, and sulfates. Thus, indirect techniques, subject to errors and assumptions, must be used. In some cases, past methods have been modified or altogether discontinued, destroying the continuity of air quality records. Finally, even where optimal levels of station coverage and sophistication of measurement pertain, one must still balance the sampling frequency and the resultant cost of data collection, storage, and processing with the budgetary constraints and potential utility of the data.

The next major step in the transition between emission levels and damages is the damage function, which relates ambient levels to resultant physical and economic damages.

3. Damage Functions

A damage function is the quantitative expression of a relationship between exposure to specific pollutants and the type and extent of the associated damage to a target population. Exposure is typically measured in terms of ambient concentration levels and their duration and it may be expressed as "dosage" or "dose". Dosage is the product of the time and ambient concentration to which the subject has been exposed, while dose, represents that portion of the dosage that has been instrumental in producing the observed damage (e.g., the amount of pollutants actually inhaled in the case of health effects of air pollution).

The damage can become manifest in a number of ways and can be expressed in either physical and biological, or economic terms. If the effect is physical: or biological, the resultant relationship is known as a physical or biological damage function, or a dose-effect function. In an economic damage function, on the other hand, the effect is expressed in monetary terms. Economic damage functions can be developed by assigning dollar values to the effects of a physical or biological damage function, or by direct correlation of economic damages with ambient pollutant levels.

In reporting a damage function, one needs to specify the pollutant, the dose rate, the effect, and the target population, or the "population at risk". Dose rate, or the rate at which ambient concentration varies with time, has a major influence on the nature and severity of the resultant effect. Long-term exposure to relatively low concentrations of air pollutants may result in manifestations of chronic disease, characterized by extended duration of development, delayed detection, and long prevalence. Short-term exposure to high concentration levels, on the other hand, may produce acute symptoms, characterized by quick response and ready detection, as well as chronic, cumulative, or delayed effects.

Specification of the population at risk involves the characterization of the nature and magnitude of the exposed population. It is crucial to this exercise for several reasons. First, it serves to define the total damages produced by a given level of exposure by multiplying the corresponding unit damage (e.g., increased mortality) for the specified population at risk (e.g., white males over 65) by the total number of units within this population. Secondly, it permits investigators to adjust their results to reflect the influence of various intrinsic (e.g., age, race, sex) and extrinsic (e.g., general health, occupation, income and education) variables in assessing the specific effects of air pollutants (e.g., increased incidence of lung cancer). Finally, it can provide useful guidance for allocating air pollution control resources by identifying areas with particularly susceptible populations exposed to relatively hazardous levels of pollutants.

A typical S-shaped damage function, showing the damage corresponding to a given exposure to a specific air pollutant, is presented in Figure A-1. The ordinate may represent either the number of individuals affected or severity of effect. The abscissa indicates the dosage in terms of time, at a given ambient concentration, or in terms of ambient concentration for a fixed period of time. The lower portion of the curve suggests that, up to a certain exposure value, known as a threshold level, no damage is observed, while the upper portion indicates that there exists a damage saturation level (e.g., death of the target population or total destruction of the crops), beyond which increased exposure levels do not produce additional damage. The middle, quasi-linear portion is very useful in that any data points here can be readily interpolated, and the frequent assumption about linearity of a damage function is most valid in this sector.

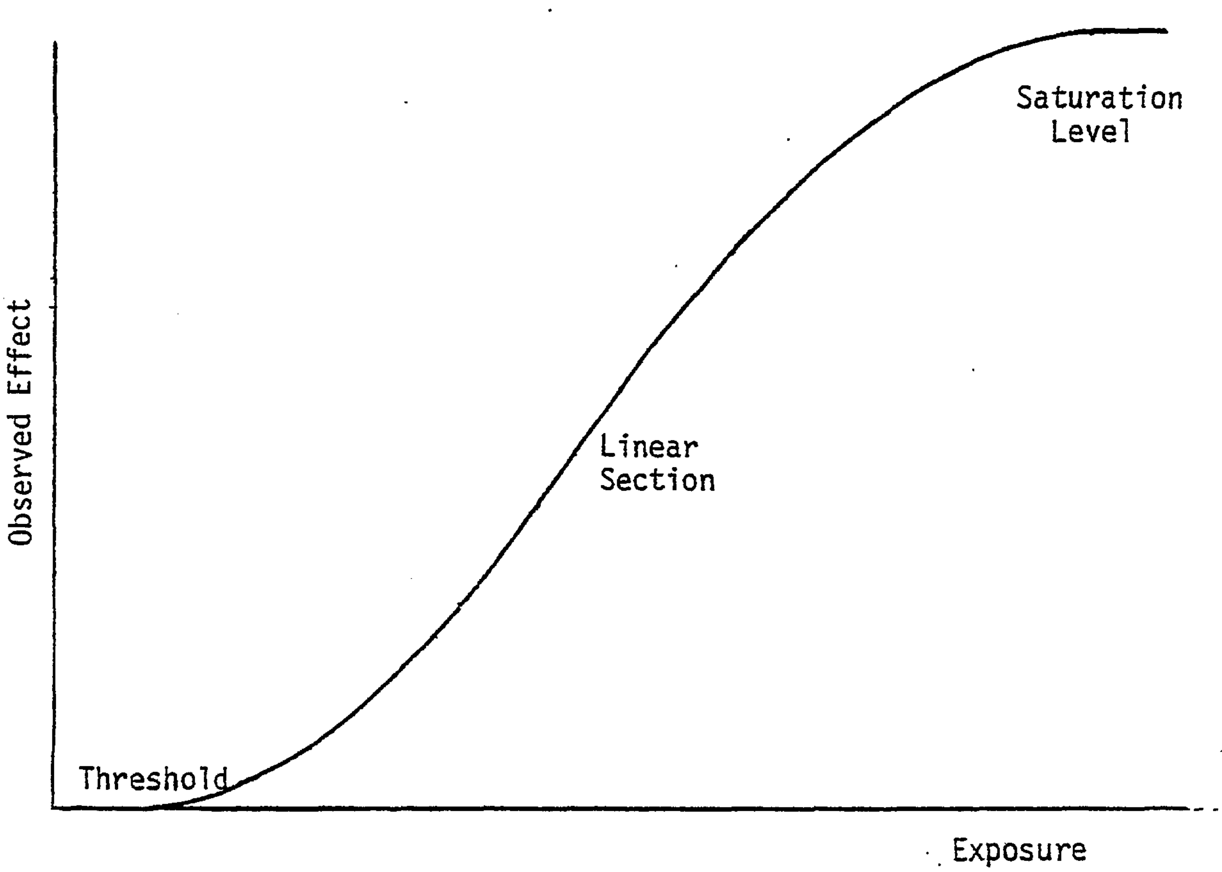


Figure A-1. Hypothetical Damage Function

The data required to develop physical or biological damage functions are obtained primarily through epidemiological, field, clinical, toxicological, or laboratory investigations. The first approach involves the comparative examination of the effects of pollutants on selected segments of population exposed to different levels of pollution, in order to deduce the nature and magnitude of the likely effect. Field observations represent a similar approach to assessment of effects on animals, vegetation, and materials, and they are characterized by similar analytical techniques and concerns. Clinical studies are based on hospital observations of the results of exposure on human subjects. Toxicological investigations involve deliberate administration of controlled doses of pollutants to animal, and occasionally, human subjects, and observation of the resulting effects. Laboratory studies represent essentially the same approach for determining effects of pollutants on plants and materials.

Several considerations need to be noted about epidemiological and field studies. First, it is very important to remove or control the influence of the various intrinsic and extrinsic variables cited above that may be responsible for the different effects observed. Secondly, epidemiological and field studies and observations can show only an association between exposure to pollution and the observed effect, suggesting the existence of a causal relationship. Such a relationship can be then tested, by toxicological and laboratory studies. It can be rendered plausible by the presentation of a plausible connective mechanism, or other weight of reason.

The common practice of setting air quality standards at, or just below the corresponding threshold levels has engendered considerable controversy. Since threshold levels are largely contingent on our ability to observe and measure small degrees of damage in large populations, they become continually eroded with improving state of the art in damage assessment. Moreover, it is known that low levels of certain pollutants which are incapable of producing measurable damages, nevertheless generate a predisposition to subsequent damage. Thus, the proponents of reduced standards advocate that these be set at 1-3 orders or magnitude below threshold levels, depending on the gravity of the corresponding damage, to ensure public safety. Opponents, on the other hand, argue that the economic costs and other deprivations associated with controls required to achieve such low standards cannot be justified.

B. DEMONSTRATION OF DAMAGE FUNCTIONS

Following this brief overview of the nature of air quality trends and damage functions, we now proceed to illustrate some of the concepts introduced and to demonstrate the interpretive utility of damage functions. These functions have been selected in the areas of health effects, vegetation injury, and material corrosion. A discussion of the function selection process precedes the presentation of the functions.

1. Selection of Damage Functions

Most damage functions in the area of human health effects are developed on the basis of epidemiological studies, which require a very substantial effort to identify a degree of damage corresponding to a given exposure to a certain air pollutant over a specified period of time. The results of this, effort may represent only one point toward the construction of a damage function for that specific health effect pollutant, dose rate, and target population. The results of other studies can contribute additional points to the construction of the same curve only if these specific conditions are sufficiently similar. Thus, one can readily appreciate that health effects damage curves are typically sketchy and unreliable.

There have been attempts to ameliorate this situation with the aid of clinical observations and toxicological investigations. Thus, a recent report for EPA by the California Air Resources Board formulated several hundred health effect damage functions on the basis of pooled expert opinions by a team of medical specialists. Toxicological investigations have been conducted on animals and, in case of the less hazardous pollutants, on human subjects. Both of these approaches involve major assumptions about the dose rate, applicability of effects on animals to human subjects, and other factors, and must be interpreted with great care.

The situation should be slightly improved in assessing damages to animal health and vegetation, because of the greater opportunity to conduct controlled experiments. It should be even better in assessing material damage, because of the additional ease of characterizing the target population. Unfortunately, the required research has. not been carried out.

Three major criteria were employed in selecting the several damage functions for the present demonstration:

- Availability of air quality trend data
- Availability of sufficient exposure-damage data
- Importance of damage

The exposure-damage data must be sufficient to construct even a rudimentary damage function. Importance of damage is measured in terms of the total loss to society, including both economic and social values.

The following functions were selected:

- Sulfur dioxide - human mortality
- Ozone - injury to tobacco leaves
- Sulfur dioxide - corrosion of zinc

Sulfur dioxide levels have been widely correlated with human health effects and the nature of this relationship has received considerable attention. The vast impact of ozone on crop yield and quality has been recognized as a result of recent discovery of high oxidant levels in rural areas and a number of yield loss experiments. Corrosion of metals is the most important component of material damages and zinc-coated steel is widely used in articles exposed to the atmosphere.

2. Effects of Sulfur Dioxide on Human Mortality

Sulfur dioxide (SO_2) was one of the first pollutants to be implicated in human health effects, and a number of investigators have sought to define its impact on human morbidity (incidence and prevalence of disease) and mortality rates. More recently, there have been indications that SO_2 has been only a proxy for a more damaging agent -- suspended sulfates (the sulfate fraction of particulates), and/or a third factor closely associated with sulfates, such as inert particulates or humidity. EPA has evolved a mathematical model of the relationship between SO_2 and sulfate levels by comparing their values in several cities. However, it should be noted that the actual relationship varies substantially among individual areas.

A composite plot of the relationship between daily sulfur dioxide levels and percent change from the mean of daily mortality rate, based on the results of two New York City studies, is shown in Figure A-2. The data appear to fall on the linear portion of the cure, and it is not clear where or whether a threshold level exists. Mortality rate changes appear both below and above the mean death rate, depending on variations of SO_2 levels with respect to the value assumed in establishing the mean death rate.

It is rather easy to find fault with the function in Figure A-2. For one thing, it attempts to correlate daily values of death rate and sulfur dioxide level, although some sort of lag time must surely be involved. It supplies no information on the many days of discomfort, disability, and other losses that obviously preceded death. It provides no characterization of the cause of death or of the population at risk, not even age, or general state of health. Yet, for all that, the function is very useful, for it provides a crude empirical estimate of the consequences of alternative pollution control actions, as well as a starting point for additional research in this area.

In addition to changes in mortality rates, air pollutant levels have been correlated with increased incidence, prevalence, and severity of various respiratory and other disorders. In particular, the aggravation and prevalence of asthma attacks by suspended sulfates at several temperature levels have been investigated by EPA's CHESS (Community Health and Environmental Surveillance System) program in a number of urban areas. Plots of this relationship for Salt Lake City and New York City are shown in Figure A-3. Unfortunately, the lack of national trend data on suspended sulfates and the uncertain relationship between sulfur dioxide and suspended sulfate levels preclude the use of these functions for interpreting the significance of air pollution trends.

The curves in Figure A-3 are known as "hockey stick" functions, because of their shape, which attempts to approximate the lower and middle portions of the classical S-curve in Figure 1. It should be noted that these plots allege the existence of a very pronounced threshold at the sulfate concentration corresponding to the intersection of the two lines. The corresponding asthma attack rate is that level which would be found even in the absence of sulfur dioxide pollution.

The trends for sulfur dioxide levels are well established and a plot of annual mean concentration in urban areas for the period 1964-1973 is presented in Figure A-4. It may be noted that SO_2 levels during that period decreased by 50 percent, from 50 to 25 $\mu g/m^3$, although individual urban areas exhibited substantial variations. According to the plot in Figure A-2, this corresponds to a 0.3 percent reduction in the mean death rate. Alternatively, if SO_2 levels were allowed to climb to the primary standard of 80 $\mu g/m^3$, one would expect an 0.5 percent increase in the death rate.

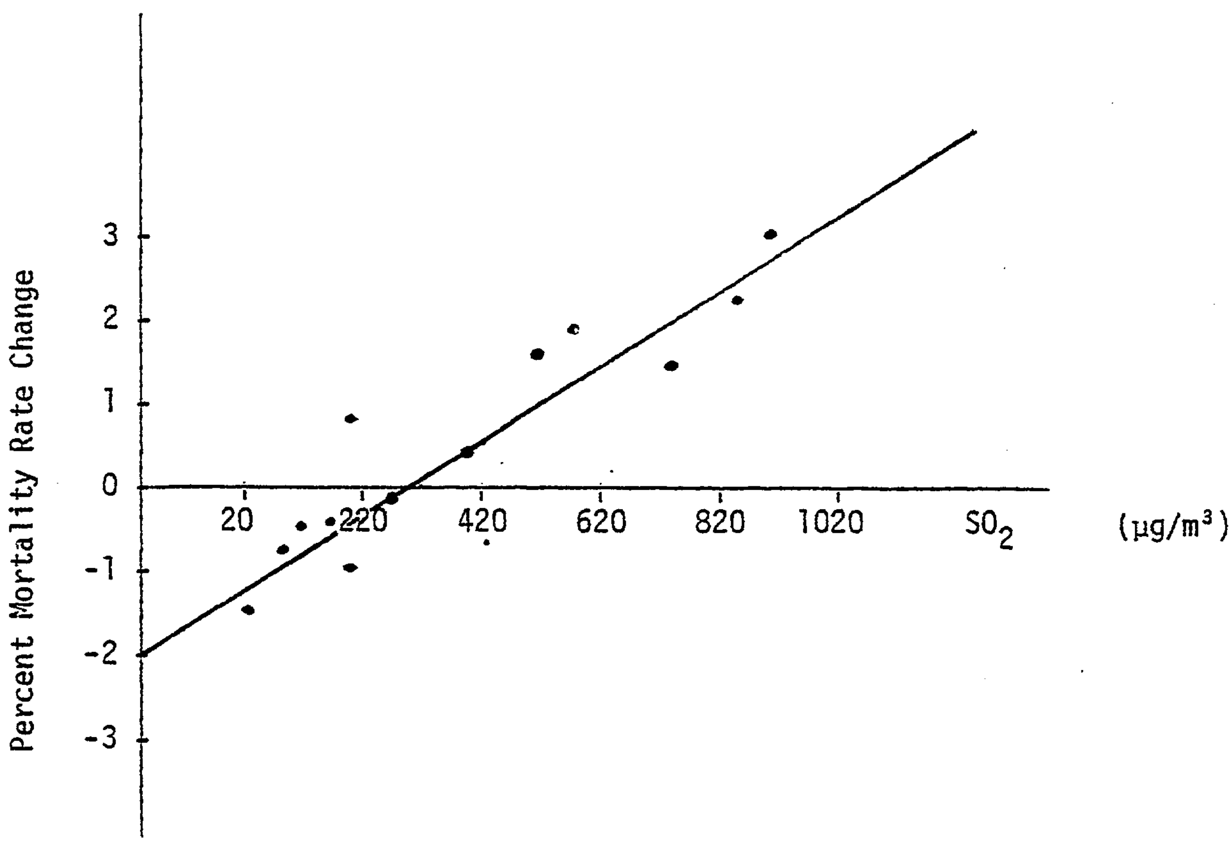


Figure A-2. Relationship Between Daily Sulfur Dioxide Levels and Daily Mortality Rates in New York City Metropolitan Area (based on Glasser and Greenberg, 1971; Buechley, 1973)

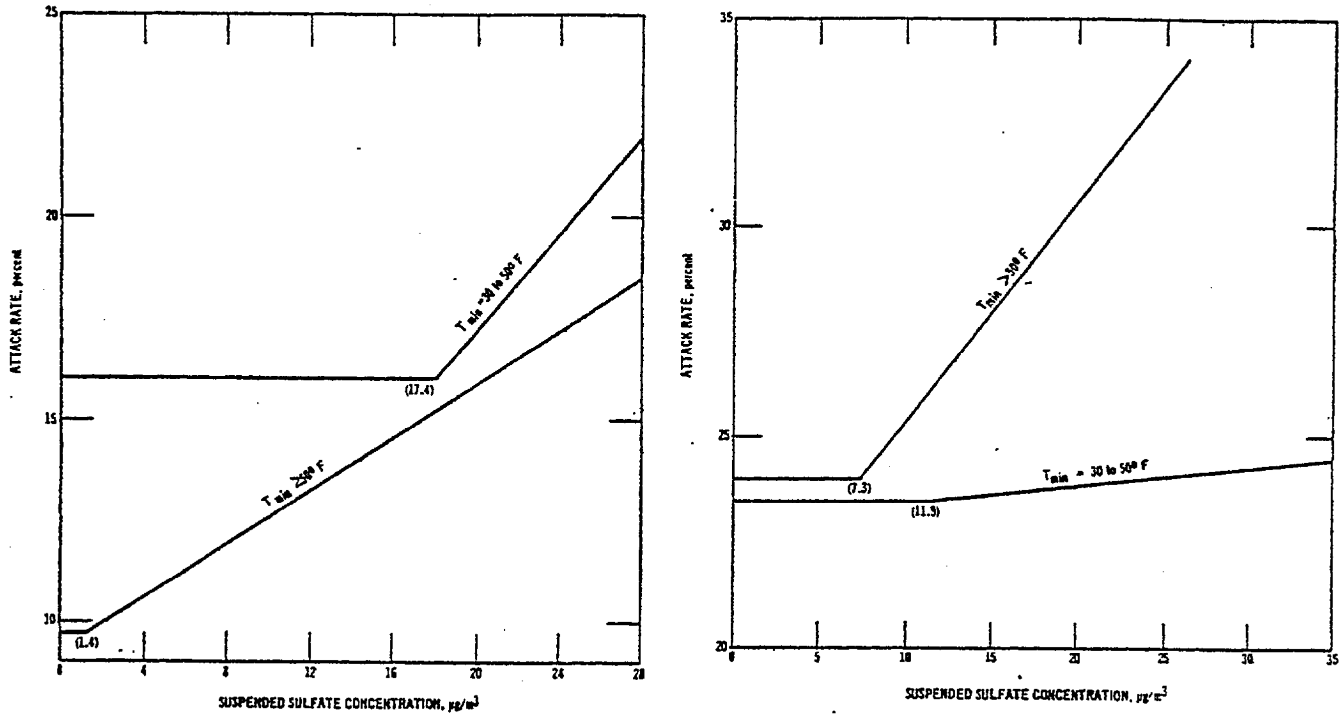


Figure A-3. Effect of Minimum Daily Temperature and Suspended Sulfates on Daily Asthma Attack Rates in Salt Lake (left) and New York (right) areas. (EPA, May 1974)

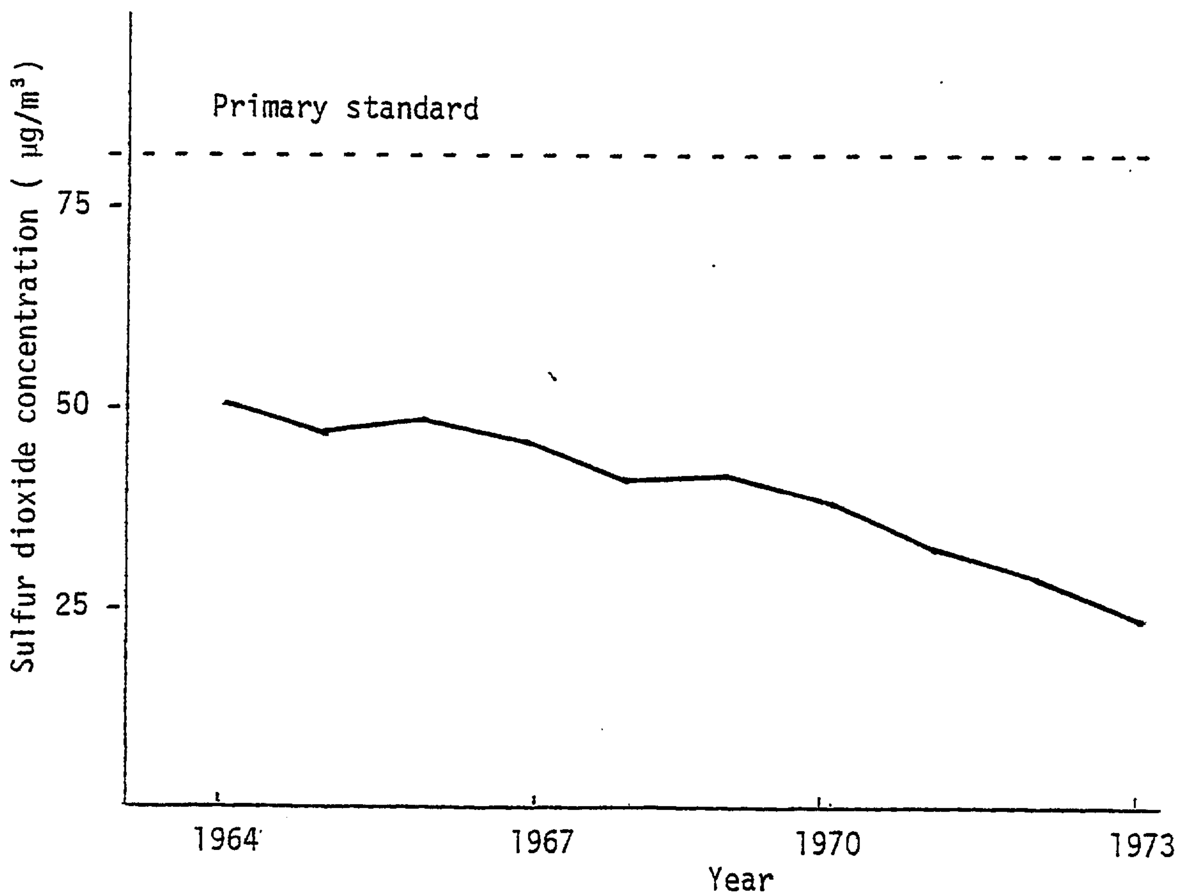


Figure A-4. National Trends of Sulfur Dioxide Levels (Annual Arithmetic Means) for 1964-1973. (Adapted from EPA, August 1973; EPA, October 1974)

There are several ways of interpreting changes in the death rate. The first logical step is to translate them into the corresponding increases or decreases in the number of deaths. Since the total annual number of deaths in the U.S. is just under 2 million, 0.3 and 0.5 percent changes in the death rate correspond to 6,000 and 10,000 annual deaths, respectively.

However, a single factor, such as air pollution, cannot be held responsible for people's deaths, but only for their premature deaths. Clearly, people would still be dying in the absence of air pollution, though hopefully at a more advanced age. Thus, the key question here is the change in life expectancy resulting from a specific change in SO_2 levels. Once this has been established, one can apply such economic factors as loss of productive days and costs of medical and hopsital, care, to compute the resultant damage to society.

3. Effects of Oxidants on Tobacco Leaves

Interest in the effects of oxidants on vegetation has been aroused recently by the discovery of high oxidant levels in rural areas and by the publications of results of controlled experiments revealing unexpectedly high yield losses attributed to oxidant exposure. In fact, EPA's draft 1975 report on the Cost of a Clean Environment places the estimate of 1973 crop losses due to high oxidant levels at nearly $3 billion.

Indications of high rural oxidant levels were discovered in 1970 by EPA in the course of investigating -injury to Christmas trees, Subsequent readings in rural areas of California, Florida, Maryland, New York, Ohio, Pennsylvania, West Virginia, and Wisconsin, confirmed that the one-hour standard of 0.08 ppm was being.exceeded frequently during the summer months. Experiments by at least a dozen teams of investigators cited in the EPA report, comparing scores of protected and exposed species of crops revealed yield losses as high as 60-70 percent at these ambient levels.

Reasonable damage functions have been developed for several plant species, such as the Bel-W_3, a sensitive variety of tobacco, which is a major agricultural crop in the southeastern states. A damage function relating exposure to oxidants, with leaf injury, an important measure of damage for the tobacco plant, was developed by Heck et al. and is pictured in Figure A-5. It may be noted that this graph provides separate plots of both the concentration and time elements of exposure, permitting the interpreation of both acute and chronic effects.

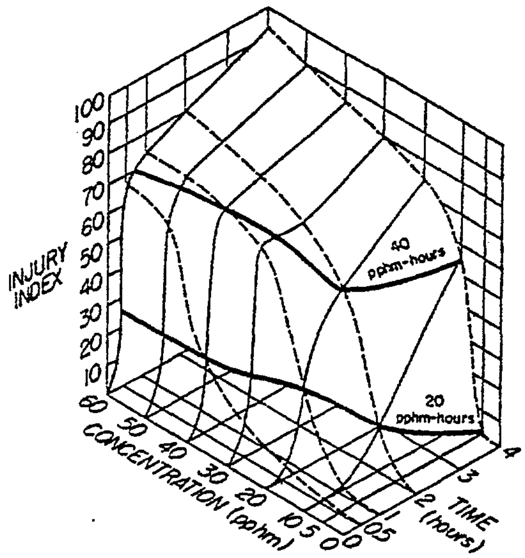


Figure A-5. Relationship Between Oxidant Exposure and Injury to Tobacco Leaf (Heck et al., 1966)

Although data on oxidant level trends in rural areas are very scarce, the graph permits speculation on the likely effects of changes in pollutant levels on the injury to tobacco leaves. For example, one can learn that, for one-hour exposures, a decrease in ozone level from 0.5 to 0.3 ppm (50 to 30 pphm) would reduce the injury index by 10 (from 73 to 63), while for one half-hour exposures, such a decrease would produce a reduction of 50 (from 62 to 12). This variation of the effect of a given dose with dose rate can be seen clearly by noting the variations of the 20 and 40 pphm-hrs plot with respect to injury index.

For all its sophistication and utility, there is much that this graphic representation does not report. There is no characterization of long-term effects of low-level exposures, though recent studies have indicated the likelihood of significant damage by prolonged exposure to levels below 0.1 ppm. Similarly, there is no information on how the impact would vary with age of the plant, an important aspect of the characterization of the population at risk. Finally, one would like to know the relative impact of other environmental variables, such as relative humidity, temperature, and sunlight.

4. Effect of Sulfur Dioxide on Corrosion of Zinc

Corrosion of metals is the most substantial component of air pollution damage to materials, accounting for over $7.6 billion in 1973. Steel, in turn, is the most widely used metal and, in many applications involving exposure to the atmosphere, steel is coated with zinc by the galvanizing process. Thus, zinc was a likely choice for illustration of pollutant damage to materials.

Once the zinc coating has been breached, the corrosion rate of the underlying steel proceeds much faster. This is due in part to the higher reactivity of steel, but also to the galvanic potential generated at the interface between the two metals.

The corrosion rate is usually influenced by humidity and temperature, as well as by sulfur dioxide. Hence, the damage function, developed by Haynie and Upham (1970) on the basis of a series of controlled experiments and shown in Figure A-6, expresses the corrosion rate of zinc as a function of an atmospheric factor, formed as a product of SO_2 concentration and a modified value of relative humidity. Thus, changes in the atmospheric factor are directly proportional to variations in sulfur dioxide levels.

For example, the 50 percent decrease in SO_2 levels between 1964 and 1973, as noted in Figure A-4, should have reduced corrosion rates from 0.8 to 0.4 μm per year, thus doubling the life expectancy of zinc surfaces.

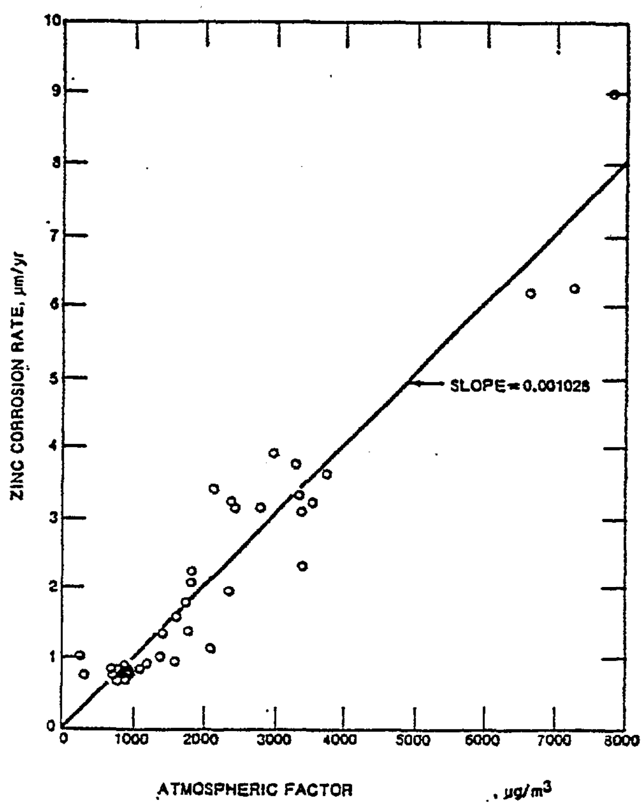


Figure A-6. Effect of SO_2 and Relative Humidity on the Corrosion Rate of Zinc (Haynie and Upham, 1970).

C. CONCLUSIONS

In spite of the large amount of effort that has been devoted to development of air pollution damage functions and compilation of air quality trends, it is fair to say that this vast, new, and promising area of investigation has been barely breached. The additional effort needed has been outlined in the introductory discussion and in the illustrative examples cited above. The potential return is impressive indeed. it promises nothing less than to provide public officials with an effective tool for allocating efficiently limited resources among the many conflicting demands for pollution control and other aspects of social welfare.

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